PhD-FSTM-2025-118
Faculty of Science, Technology and Medicine

Dissertation

Defence held on 24 October 2025 in Luxembourg

to obtain the degree of

DOCTEUR DE L'UNIVERSITÉ DU LUXEMBOURG EN SCIENCES DE L'INGÉNIEUR

by

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FRAMEWORK FOR ASSESSING TECHNICAL AND BEHAVIOURAL MEASURES TO REDUCE CARBON EMISSIONS IN OLDER EDUCATIONAL BUILDINGS IN LUXEMBOURG

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- is not substantially the same as any other that I have submitted, and;
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With my approval I furthermore confirm the following:

- I have adhered to the rules set out in the University of Luxembourg's Code of Conduct and the Doctoral Education Agreement (DEA)[1], in particular with regard to Research Integrity.
- I have documented all methods, data, and processes truthfully and fully.
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Acknowledgment

This thesis is the result of my work as a doctoral researcher at the University of Luxembourg, during which I contributed to four Interreg projects – ENERGE, Gencomm, GreenSKHy and CERTEB-OPT. I would like to express my heartfelt gratitude to everyone who, in one way or another, contributed to the completion of this research project, whether through active collaboration or by offering much-needed personal support throughout these four years.

Firstly, I wish to thank my academic supervisor, Stefan Maas, for not only entrusting me with this project, but also for his guidance, encouragement, and support throughout my doctoral journey. I am also grateful to my dissertation supervisory committee (CET), Stephan Leyer and Manfred Greger, for their valuable input and fruitful discussions over these years. I would also like to extend my thanks to Edelle Doherty and Bodo Gross for the enriching collaboration during our joint projects, and for kindly agreeing to serve as jury members on my Defence Committee.

My gratitude extends to the University staff from the laboratory, infrastructure, sustainability, and administrative teams for their continuous support. I am equally thankful to the partners from the ENERGE and Gencomm projects for sharing their knowledge and experience, to the Lycées and their staff for their close cooperation, warm welcome, and hospitality, and to the Administration des Bâtiments Publics for kindly providing access to the building data. I also wish to thank Anna Kornadt and her team for their guidance on the behavioural approach, as well as the students I supervised during this period, whose contributions were essential to the development of parts of this work.

A special thanks goes to my colleagues who, beyond sharing knowledge, stood by me during challenging moments and celebrated achievements. I am equally thankful to my dear friends and family around the world, who patiently listened and supported me during long calls, as well as those in Luxembourg who looked after my family and helped make this period smoother and more enjoyable.

Finally, my deepest gratitude is reserved for my family. I thank my parents and grandparents for showing me that the world is ours to explore, that there are no limits to our dreams, and for providing me with every opportunity to pursue them. I am especially grateful to Carlos for his unconditional support, and to Melissa and Isabella for reminding me of what truly matters in life and for giving me the strength to go further.

Abstract

Globally, the impacts of climate change are increasingly evident, yet the decarbonisation of the building sector continues to face delays. Older educational buildings, constructed before energy efficiency standards and facing uncertain long-term use, pose particular challenges. Interventions in these buildings must not only be technically effective but also adapted to their specific context, carefully implemented, and evaluated across their lifecycle in terms of energy, carbon, and occupant comfort, while also convincing stakeholders of their value.

Despite extensive research, assessing the real impact of interventions remains difficult, hindered by limited representative data, due to the persistent performance gap between expected and measured energy and carbon savings. Furthermore, much of the building stock continues to struggle with improving energy performance, making the large-scale adoption of effective measures challenging. These challenges underscore the need for a practical, integrated approach that combines technical and behavioural strategies, while also introducing clear decision-making tools.

This study proposes a four-step methodology to reduce energy consumption and carbon emissions in educational buildings in Luxembourg, integrating both technical and behavioural approaches to identify high-impact savings opportunities without major renovations while maintaining user comfort. The steps include: (1) stakeholder-driven behavioural analysis to encourage engagement and support implementation; (2) energy auditing to characterise baseline performance and highlight easy-to-leverage savings; (3) the selection and implementation of targeted interventions across four categories, (a) operational adjustments through reduced operational modes, (b) sufficiency measures requiring no direct investment, (c) pinpointed renovations to reduce heat losses, and (d) renewable energy integration; and (4) performance evaluation through energetic, carbon, economic, and comfort assessments, culminating in an indicator to prioritise interventions based on their costs for avoided carbon emissions.

Results demonstrate that meaningful reductions of carbon emissions can be achieved without compromising occupant comfort. The methodology provides a replicable framework for similar buildings, balancing technical efficiency, behavioural engagement, and practical feasibility, and offers valuable guidance for future energy- and carbon-saving strategies in the educational sector.

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Abbreviations

ABP - Administration des Bâtiments Publics
ACC - avoided carbon cost
ANA - above national average
BNA - below national average
CFPP - cold fuel properties
CHP - combined heat and power
DIN - German Industrial Standard
EHB - European hydrogen backbone
EIGA - European Industrial Gases Association
EMS - energy management system
ENNOH - European Network of Network Operators for Hydrogen
EPBD - Energy performance of buildings directive
EPD - environmental product declaration
EU - European Union
GFA - gross floor area
GHG - greenhouse gas
HDD - heating degree days
HHV - higher heating value
HVAC - heating, ventilation and air conditioning
HVO - hydrotreated vegetable oil
IPCC - Intergovernmental Panel on Climate Change
IPCEI - Important Projects of Common European Interest
ISO - International Organization for Standardization
ITM - Inspectorate of Labour and Mines in Luxembourg
LCEA - life cycle energy analysis
LHV - lower heating value
MON - motor octane number
NDIR - non-disruptive infrared technology
NECP - national energy and climate plans
NTC - negative temperature coefficient
NTP - normal temperature and pressure conditions
NZEB - nearly zero energy building
PEB - pro-environmental behaviour
PENRT - total use of non-renewable primary energy resources
PMV - predicted mean vote
PPD - predicted percentage of dissatisfied
PVC - polyvinyl chloride
RED - renewable energy directive
RON - research octane number
SCRB - Service de Contrôle et de Réception du Bâtiment
SIA - standards of the Swiss society of engineers and architects
XPS - extruded polystyrene

Symbols

a	beginning of baseload occurrence [h]
α_i	internal surface heat transfer coefficient [W/m^{2}K]
A_E	surface area of the building envelope [m^2]
A_F	net floor area of the building [m^2]
ACC	avoided carbon cost [€/kgCO$_2$]
$Annual\ Cash\ Flow$	annual cash flow generated by the energy savings
b	end of baseload occurrence [h]
$C(t)$	concentration variation over time t [ppm]
C_0	initial CO_2 concentration [ppm]
C_{t_1}	CO_2 concentration at time t_1 [ppm]
$Carbon\ compensation\ time$	time necessary for operational carbon savings compensate the added embodied carbon [years]
CO_2	carbon dioxide
d	thickness of the layer [m]
E_{bl}	baseload consumption [kWh/a]
E_{losses}	heat loses [kWh/m^2]
E_{norm}	normalised annual thermal energy consumption of the building for average climate conditions [kWh]
E_{year}	measured thermal final energy consumption of a specific year [kWh]
$Embodied\ carbon\ emissions$	embodied carbon equivalent emissions [kgCO$_2$]
$Energy\ compensation\ time$	time necessary for energy savings compensate the added embodied energy [years]
$Energy\ cost$	specific energy cost [€/kWh]
e	protection class coefficient defined on the RGD 2021
$E_{f\,saved_i}$	saved final energy type i [kWh]
$E_{p\,\mathrm{embodied\ energy}}$	primary embodied energy [kWh$_p$]
$E_{p\,saved}$	yearly saved operational primary energy [kWh/a]
$E_{p\,saved_i}$	saved primary energy [kWh$_p$]
e_p	weighted primary energy factor
$e_{CO_2\,natural\,gas}$	environmental factor for district heating with combined heat and power systems operating with natural gas
$e_{CO_2\,wood\,pellets}$	environmental factor for district heating with combined

	heat and power systems operating with wood pellets
e_{CO_2w}	weighted environmental factor
$e_{CO_{2i}}$	environmental factor for final energy type i [kgCO2/kWh]
$e_{p\ natural\ gas}$	primary energy factor for district heating with combined heat and power systems operating with natural gas
$e_{p\ wood\ pellets}$	primary energy factor for district heating with combined heat and power systems operating with wood pellets
e_{p_i}	primary energy factor type i [kWhp/kWh]
f_{cl}	clothing surface area factor
H_2	hydrogen
h_c	convective heat transfer coefficient [W/m²K]
HDD_m	mean Heating Degree Days for a long period of time in this region [Kd]
HDD_{year}	Heating Degree Days of the analysed year [Kd]
HDD_{year_n}	Heating Degree Days of each year in the historical period [Kd/a]
I_{cl}	clothing insulation [m²K/W]
$Investment$	investment [€]
M	total energy radiated per unit of surface [W/m²]
Met	metabolic rate [W/m²]
NO_x	nitrogen oxides
n	number of years in the historical period [-]
n_{50}	number of times that the air changes per hour at 50 Pa [1/h]
$n_{natural\ gas}$	part the heat produced from natural gas
$n_{wood\ pellets}$	part the heat produced from wood pellets
n_{decay}	air exchange rate CO_2 concentration decay method [1/h]
n_t	air exchange rate at a time t [1/h]
$Op\ years$	number of operational years considered for the building in the analysis [years]
$Operational\ carbon\ savings$	yearly saved operational carbon emissions [kgCO2/a]
$Payback\ Time$	period required to recover the initial investment [years]
$P(t)$	power [kW]
PMV	predicted mean vote [-]
PPD	predicted percentage of dissatisfied [%]

p_a	water vapour partial pressure [Pa]
$\dot{q}$	heat flux density [W/m^2]
q_{50}	air permeability at 50 Pa [m^3/m^{2}h]
R	thermal resistance of the building component with internal and external thermal resistances [m^{2}K/W]
R_n	thermal resistance of each layer of the building component [m^{2}K/W]
R_{se}	external thermal surface resistance [m^{2}K/W]
R_{si}	internal thermal surface resistance [m^{2}K/W]
σ	Stefan-Boltzmann constant $5{,}67 \times 10^{-8}$ [W/m^{2}K^4]
t	period [h/a]
t_a	air temperature [°C]
t_{cl}	clothing surface temperature [°C]
t_0	time at the beginning of the measurements [h]
t_1	time at the end of the measured period [h]
$\overline{t_r}$	mean radiant temperature [°C]
T	temperature [K]
T_e	external air temperature [K]
T_i	internal air temperature [K]
T_{se}	external surface temperature [°C]
T_{si}	internal surface temperature [K]
U	thermal transmittance [W/m^{2}K]
U_c	thermal transmittance of the building component [W/m^{2}K]
V	heated net volume [m^3]
$\dot{V_{fan}}$	airflow needed to create a change in building pressure of 50 Pa [m^3/h]
v_{ar}	relative air velocity [m/s]
w_{50}	leakage flow rate at 50 Pa [m^3/m^{2}h]
W	effective mechanical power [W/m^2]
$Yearly\ carbon\ savings_i$	yearly carbon savings for final energy type i [kgCO_2]
$Yearly\ energy\ savings_i$	yearly energy savings for final energy type i [kWh]
$Yearly\ savings$	yearly reduction in energy bills [€/year]

1. Introduction

The European Union (EU) has set ambitious climate objectives through the European Green Deal, aiming to transform the EU into a climate-neutral economy by 2050. Central to this vision is the target of reducing greenhouse gas (GHG) emissions by 55% compared to 1990 levels by 2030, 90% by 2040, and achieving full climate neutrality by mid-century [1]. This is important considering that operations of buildings account for 40% of the European final energy consumption [2].

To address this challenge, the EU has implemented the Energy Performance of Buildings Directive (EPBD), with the objective of fully decarbonising the building stock [3]. The directive establishes rigorous minimum energy performance requirements for both new and existing buildings, with recent revisions mandating zero-emission standards for new constructions and prioritising renovations of the least energy-efficient buildings [4]. These requirements, however, often increase the embodied energy of the building through the renovation processes [5]. Furthermore, the real impact of these measures is limited, as demonstrated by the difference between calculated energy performance and actual energy consumption in buildings, referred to as the performance gap [6].

In addition to the physical performance of buildings and their technical systems, significant potential for energy savings is found in optimising building operation. A recurrent challenge pertains to the discrepancy between actual demand and energy consumption. This discrepancy is especially evident in non-residential buildings, where user control is frequently constrained and decision-making is disseminated across multiple stakeholders [7]. It is evident that facility managers, tend to prioritise operational settings that ensure uninterrupted functionality and occupant comfort, often to prevent user complaints, over configurations that maximise energy efficiency.

Further reductions in carbon emissions within the building sector can be achieved through the integration of renewable energy sources. The overall effectiveness of these measures depends on the type of renewable technology adopted, the production processes involved, and the characteristics of the feedstocks used. While some renewable solutions can be implemented with relative ease, others still require substantial investment and infrastructural adaptation. Nevertheless, the growing European incentives to drive the energy transition are gradually reducing the financial and infrastructural barriers, fostering the conditions for these renewable technologies to become broadly accessible and widely adopted.

In this context, the objective of this research is to develop, demonstrate and assess practical solutions for reducing energy consumption and associated carbon emissions in educational buildings in Luxembourg, built before 1990 and without major renovations, while preserving comfort levels for users. The study proposes an interdisciplinary, four-step framework that integrates both technical and behavioural strategies, engaging the diverse chain of stakeholders in identifying savings opportunities and defining interventions to enhance acceptance. The evaluation of the implemented measures, considering energy performance, carbon emissions, economic feasibility, and user comfort, offers a reference for improvement and provides a replicable model for similar buildings across the EU.

The EPBD recognises the strategic role of public buildings in leading by example. Due to their visibility and capacity to influence societal behaviour, they can act as catalysts for sustainable practices [3]. Educational buildings, in particular, hold a unique potential to spread awareness and best practices in energy efficiency and reducing carbon emissions into households and communities over the long term.

This study begins with a literature review (**Chapter 2**) that examines the policy framework, current solutions for reducing energy use in existing buildings, with a focus on educational facilities, and the challenges they face. It then presents the adopted methodology (**Chapter 3**), including the proposed framework, which is structured into four sequential steps. Step 1 introduces the behavioural approach (**Chapter 4**), involving stakeholders in identifying and addressing operational inefficiencies. Step 2 details the energy audit process to characterise baseline performance and identify easy to leverage savings opportunities (**Chapter 5**). Step 3 outlines the implementation of energy- and carbon-saving interventions (**Chapter 6**), combining operational adjustments, pinpointed renovations and the integration of renewables. Step 4 assesses the performance of these interventions in terms of energy, carbon emissions, cost-effectiveness, and user comfort (**Chapter 7**). Finally, the conclusion synthesises the key findings (**Chapter 8**), highlights the implications for policy and practice, and provides recommendations for replication in other contexts.

2. Literature review

Reducing the energy demand and carbon emissions of buildings is central to climate-neutrality goals, yet progress remains constrained by persistent barriers. Efforts have traditionally focused on physical retrofits to enhance performance, but these often require substantial embodied energy and do not always deliver the expected results. Meanwhile, relatively simple operational measures, such as aligning system setpoints with actual demand, are frequently overlooked, despite their potential to achieve savings with minimal investment. When interventions are implemented, their effectiveness is frequently compromised by the well-documented performance gap between predicted and measured outcomes, driven by uncertainties in modelling parameters, variations in construction quality, inefficient system operation, and user behaviour. Considering and addressing this gap is therefore essential to ensure that energy-saving measures, whether refurbishments or replacements, deliver reliable and effective results [6].

The adoption of renewable energy sources offers additional opportunities to reduce reliance on fossil fuels. Photovoltaic systems are becoming increasingly common, while options such as hydrogen or alternative fuels like hydrotreated vegetable oil (HVO) remain underexplored in the building sector.

Educational buildings illustrate these issues, since a share of the stock was constructed before the introduction of efficiency standards, and many facilities operate with constrained budgets or face uncertain long-term use. Their diverse mix of users and decision-makers creates barriers not only to adopting interventions but also to sustaining them over time. These barriers are accentuated by the absence of clear, integrated decision-making tools that would enable stakeholders to compare options in terms of lifecycle energy and carbon performance, economic feasibility, and occupant comfort.

This chapter reviews these challenges with a focus on educational buildings. It examines the potential of operational optimisation, the role of targeted retrofit measures, the promise of renewable energy integration, and the influence of behavioural and organisational factors on implementation. By highlighting the barriers that reduce effectiveness and the gaps in existing evaluation practices, the chapter establishes the foundation for the four-step framework. The present framework, developed in this research, combines stakeholder engagement, energy auditing, targeted interventions, and integrated performance assessment to improve both the impact and replicability of energy-saving strategies in the educational sector.

2.1. Life cycle energy analysis of buildings

Life cycle energy analysis (LCEA) is a methodology for evaluating the total energy consumption of buildings across all phases, from material extraction to demolition, as shown in **Figure 2.1**. This cycle is composed of four phases:

- the pre-use phase (A), corresponding to the energy necessary to produce and transport the building materials, construction and renovations;
- the use phase (B), which is the energy required for the operation of technical installations and appliances;
- the end-of-life phase (C), covering the demolition, and the energy necessary to transport, dispose or recycle the materials;
- the fourth phase is optional phase (D), that is related to potential benefit and loads beyond the system, referring to reuse, recovery and recycling.

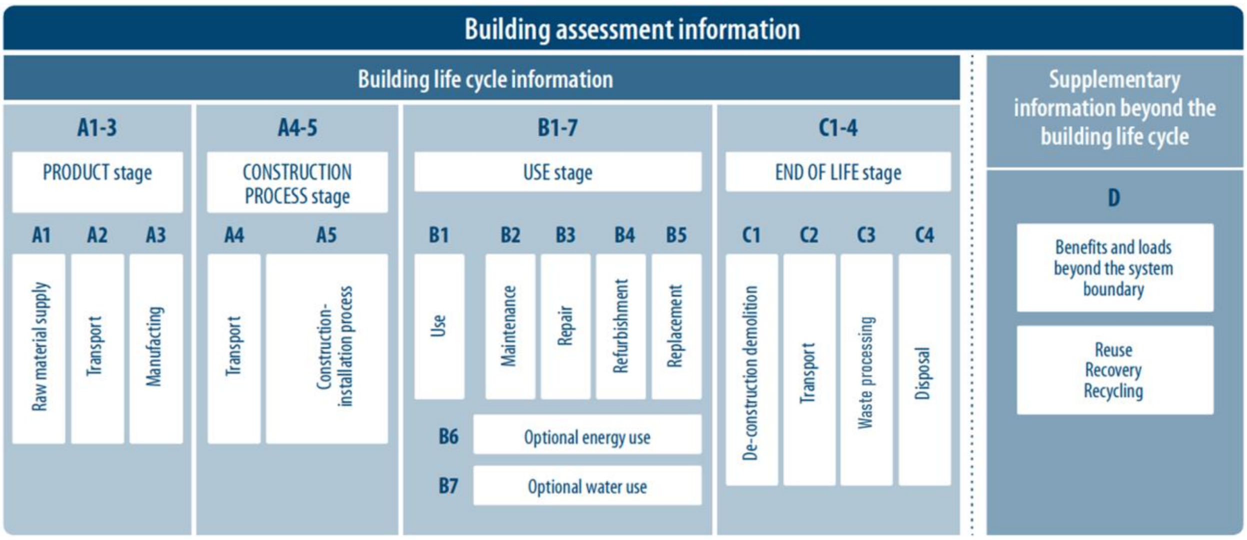


Figure 2.1: Life cycle phases considered in the life cycle energy analysis of buildings [8]

The two first phases (A and B), characterised by the pre-use and use stages, together almost the entirety of the energy requirement over the life cycle, representing between 10% to 20% and 80% to 90% respectively [9]. Studies show that transport (A2, A4, and C2), construction (A5), and demolition and disposal (C1, C3, and C4) have very low influence on the overall results. Reported values in the literature indicate that construction accounts for only 0.2% to 1% of the total life-cycle energy use, while demolition contributes between 0.1% and 3% [5][10].

A recent systematic review realised by Dahiya et al. (2024), identifies that LCEA remains a resource-intensive process due to incomplete inventory databases and inconsistent methodologies, which prevent result comparability, such as the adoption of different life spans in the analysis [11].

The introduction of the Energy Performance of Buildings Directive (EPBD) and subsequent updates have set progressively higher standards for insulation, heating systems, and overall energy efficiency, leading to an overall tendency to reduce the energy consumption during the operation phase, as shown in **Figure 2.2**. Mandatory energy performance certificates, stricter requirements regarding the energy performance of buildings, and incentives for renovations have driven improvements in both new and existing structures. Moreover, the additional reductions in final recorded energy consumption observed in **Figure 2.2** are attributable to the introduction of renewable energy sources. While this process has the potential to significantly reduce carbon emissions, it does not guarantee an improvement in energy efficiency. Therefore, it is important to distinguish between the impacts in carbon emissions and the reduction in final energy consumption, in order to avoid the potential misinterpretation regarding the efficacy of performance.

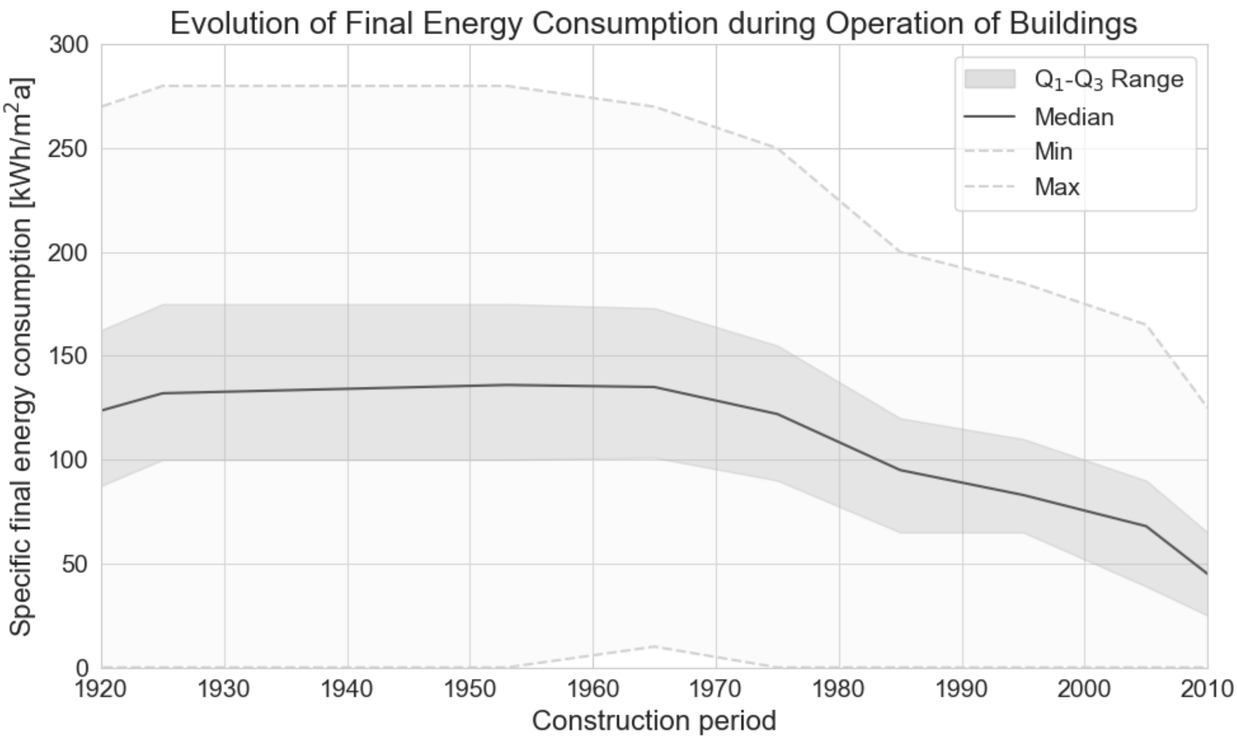


Figure 2.2: Evolution of the measured specific final energy consumption for thermal use in residential buildings energy over the years, developed based on information from GAPxPLORE [12]

Life cycle energy analysis has consistently shown that while operational energy historically dominated total building energy use, embodied or grey energy, referring to the energy content of the building components, is becoming increasingly significant. The improvement of the building envelope reduces the energy losses over operation, however, it requires more materials, and thus, it increases the energy used during the construction [11]. Consequently, non-material interventions centred on optimised operations should be prioritised, as explored in the four-step framework, presented in this thesis.

Chastas et al. (2016) and Dilsiz et al. (2019) analysed the energy shares of 100 residential and commercial buildings, highlighting a shift from operational to embodied energy with stricter regulations regarding the building envelope. Their results show that the operational energy share decreases from 96%–48% in conventional buildings to 81%–40% in low-energy buildings, with even lower shares observed for nearly zero-energy buildings (NZEBs). At the same time, their findings also indicate that this trend is not always beneficial. For example, in passive buildings, the overall life-cycle energy demand can exceed that of low-energy buildings [5][13].

Although operational energy tends to be reduced in better insulated buildings, the significantly higher embodied energy content of their construction materials may take approximately 20 years for the operational savings to compensate for the initial higher investment [14]. This long period highlights that replacing existing buildings is not always the best strategy, reinforcing the case for prioritising non-material interventions and pinpointed renovations.

A similar situation arises at the component level, where strategies that rely on increasingly large quantities of material may inadvertently increase embodied energy to the extent that it counteracts the operational benefits. Because the relationship between insulation thickness and thermal losses is non-linear, largely due to convective effects, the first centimetres of insulation have the greatest influence on reducing heat losses. Beyond a certain thickness, however, additional insulation provides only marginal improvements in the component's overall thermal resistance [15][16][17][18][19]. Delmonte et al. (2024) show that energy-intensive insulation materials, even when characterised by low thermal conductivity, can ultimately increase total energy consumption once this threshold is exceeded [20].

The optimal thickness of four insulation materials in heat-pump-heated buildings in Luxembourg is evaluated based on three scenarios (conservative, realistic, optimistic). The study calculated total primary energy as a function of insulation thickness, accounting for material properties, heating demand, and system efficiency. As demonstrated in **Figure 2.3**, results highlight that energy savings are most significant in the first few centimetres of insulation, while materials with high grey energy, such as calcium silicate, may offset operational savings. These outcomes demonstrate the importance of considering the full life cycle rather than operational energy alone when planning energy-efficient renovations [20].

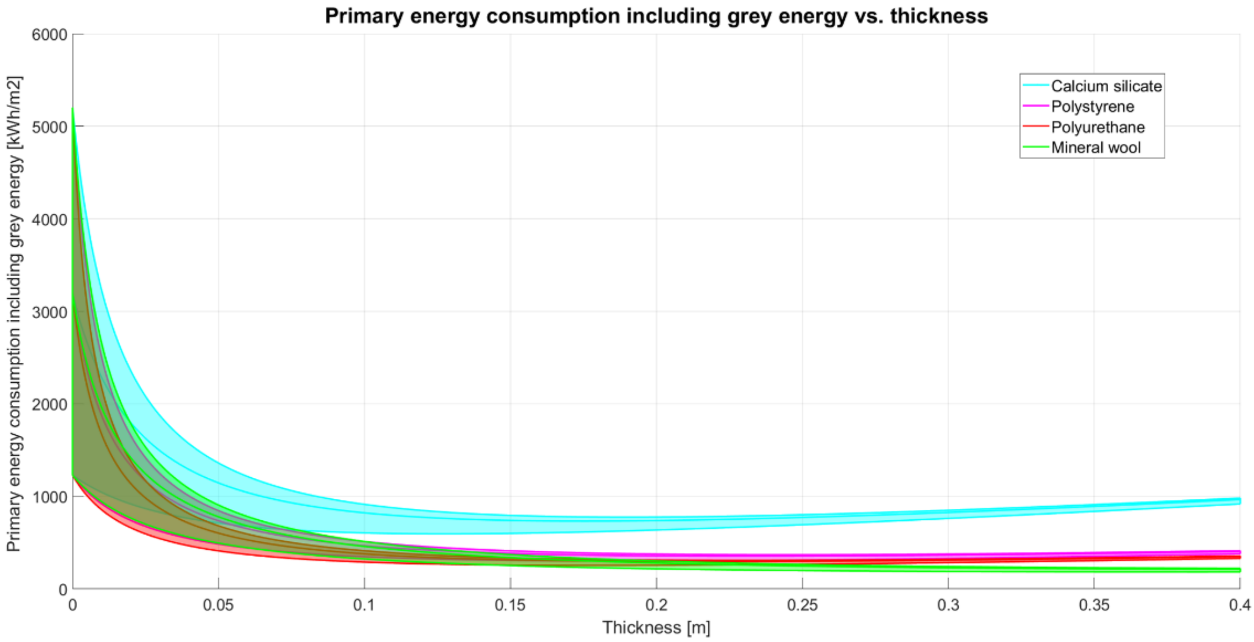


Figure 2.3: Total primary energy including grey energy for all scenarios and insulation materials [20]

The effect of increasing the overall energy intensity of buildings, while implementing measures to reduce their operational requirements is also observed in the context of deep renovations. A comprehensive study on European building renovations has demonstrated that while operational CO_2 reductions are significant, embodied emissions from construction materials remain a critical challenge [21]. These findings underscore the need to balance embodied and operational energy, and the need to prioritise low-cost behavioural and operational interventions, such as those that emerge from the four-step framework proposed in this study.

2.2. Energy Performance gap

Regulations regarding energy efficiency of buildings require performance assessment of new and existing buildings. There are several available standardised methods using steady-state or dynamic calculations to estimate the energy demand of buildings. However, a performance gap is extensively observed between the simulated and the measured consumptions [22]. A literature review conducted by Dronkelaar et al. (2016) concerning the energy performance gap and its underlying causes included 62 non-residential buildings and demonstrated that, on average, their measured consumption was 34% higher than predicted. The researchers identified three primary causes for these discrepancies: uncertainties during the modelling process (20% to 60%); occupant behaviour (10% to 80%); and inappropriate operation (15% to 80%) [6]. In Switzerland, the GAPxPLORE project (Cozza et al., 2019) identified uncertainties with regard to the modelling parameters, changes to the design during execution, the faulty or inappropriate operation of technical equipment and monitoring systems, and occupant behaviour, as the most frequent causes for the energy performance [12].

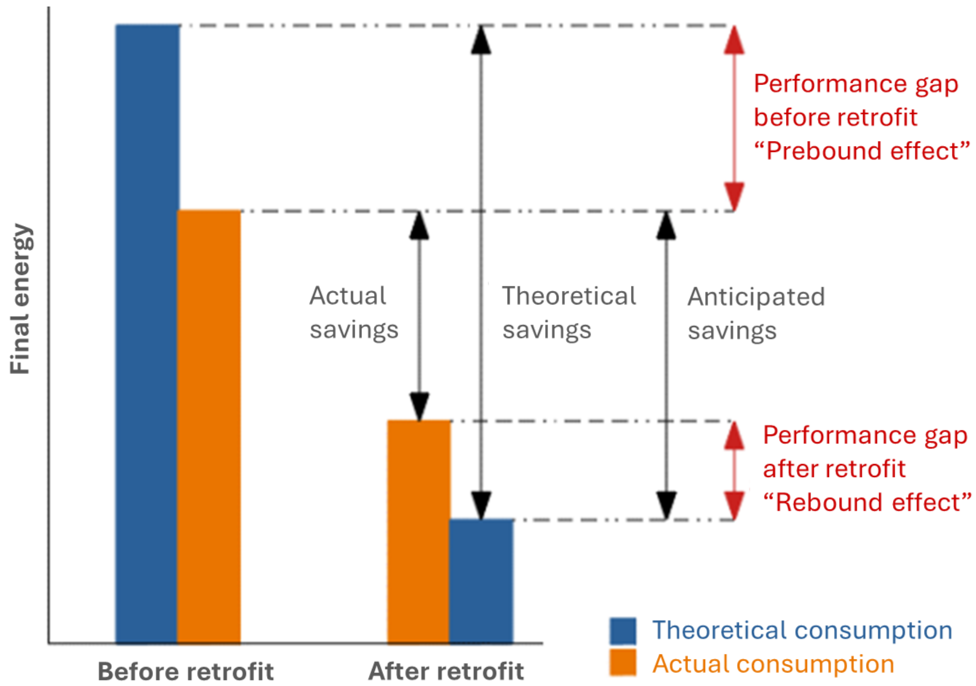


Figure 2.4: Differences between theoretical and actual energy consumption, before and after energy retrofit [12]

The aforementioned discrepancies are described as the prebound and rebound effects, as the performance gap before and after retrofit, respectively. These effects are presented in **Figure 2.4** from the GAPxPLORE project. The prebound effect is defined as the phenomenon in which the measured energy utilisation is found to be lower than the predicted value. This occurrence is most commonly observed in older buildings, where parameters are incorporated into simulation models, using lower performances than reality. The rebound effect refers to the difference between the calculated improvements related to renovations and the actual consumption [12].

In the process of planning energy efficiency and carbon reduction measures, understanding these effects is necessary in order to implement effective, real-impact solutions, rather than merely theoretical ones.

Errors in the estimation of building envelope characteristics, such as thermal transmittance, air change rates, and thermal bridges, often result in inaccurate energy predictions. The responsibility for the proper assessment of such errors remains that of the certifying expert. Inaccurate estimations of heating system losses, including production, distribution, emission, and control losses, can further compromise the accuracy of predicted energy consumption. Assumptions regarding indoor temperatures, such as the 20°C standard in Luxembourg, are inadequate in capturing seasonal or spatial variations within buildings, particularly when comparing older and newer constructions. Moreover, the incorporation of active systems, such as ventilation or climate control, frequently results in an increase in primary energy consumption without a concomitant improvement in comfort. It has been demonstrated by means of parameter studies that the design of HVAC systems which is not efficient can result in cumulative, non-linear energy penalties. With regard to the impact of occupant behaviour, Maas et al. (2008) indicate that two-thirds of households exhibit energy consumption that falls within ±33% of the mean. The findings indicate that, while this alone cannot account for the systematic differences between calculated and measured values, there is significant potential for users to achieve substantial savings if they are provided with targeted information regarding sensitive parameters [23].

Xu et al. (2021) conducted a study concerning the impact of stakeholders on the energy performance gap. The study revealed that owner and energy managers were identified as impactful stakeholders. However, poor collaboration and communication, as well as insufficient knowledge and experience, were also cited as significant issues. These findings underscore the significance of effective collaboration in achieving results [7].

These findings highlight the importance of a structured approach for reducing energy consumption in buildings. In this context, the four-step framework proposed in **Chapter 3** is designed to systematically identify the complex stakeholder chain and actively engage them in the process. It employs energy audits based on stationary energy balance methods, developed with a judicious selection of input parameters, to detect deviations in building operation, and low energetic performances. This approach combines simulation-based predictions with consumption-based references from the literature to evaluate the efficiency of individual buildings and to identify potential energy-saving opportunities. Finally, the framework allows for the implementation of these measures and the evaluation of their impact.

2.2.1. Existing buildings

The analysis of 50.000 existing buildings, part of a Swiss project called GAPxPLORE, shows that the energy performance gap between calculated and measured energy consumption data is more expressive in the lower performance, and older buildings [12]. This pattern is also clearly observed in a study concerning the calculated and measured final energy consumption in residential buildings in Luxembourg [24].

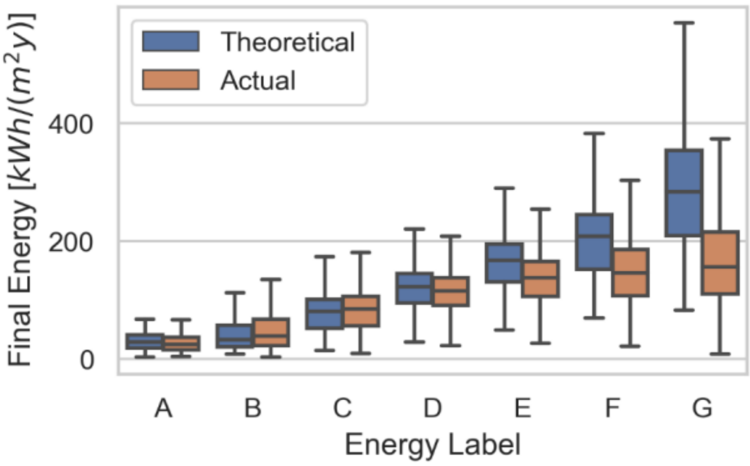


Figure 2.5: Theoretical and actual consumption of final energy for thermal use in residential buildings per energy label [12]

As it is shown in **Figure 2.5**, the buildings labelled between D and G present lower measured consumption than the simulated values. Moreover, it is possible to notice that the gap increases towards the lower performance labels, showing that the theoretical values regarding these buildings lead to higher discrepancies, such as median gap values reaching up to 40,4%. Furthermore, similar median variations are observed in class B and E, however label B buildings consume more than calculated, while label E buildings consume less than expected. The study also shows that the thermal consumption of older buildings from before the year 1990 are more negatively impacted by the energy performance gap, while buildings from after the year 2000 tend to consume more than simulated [12].

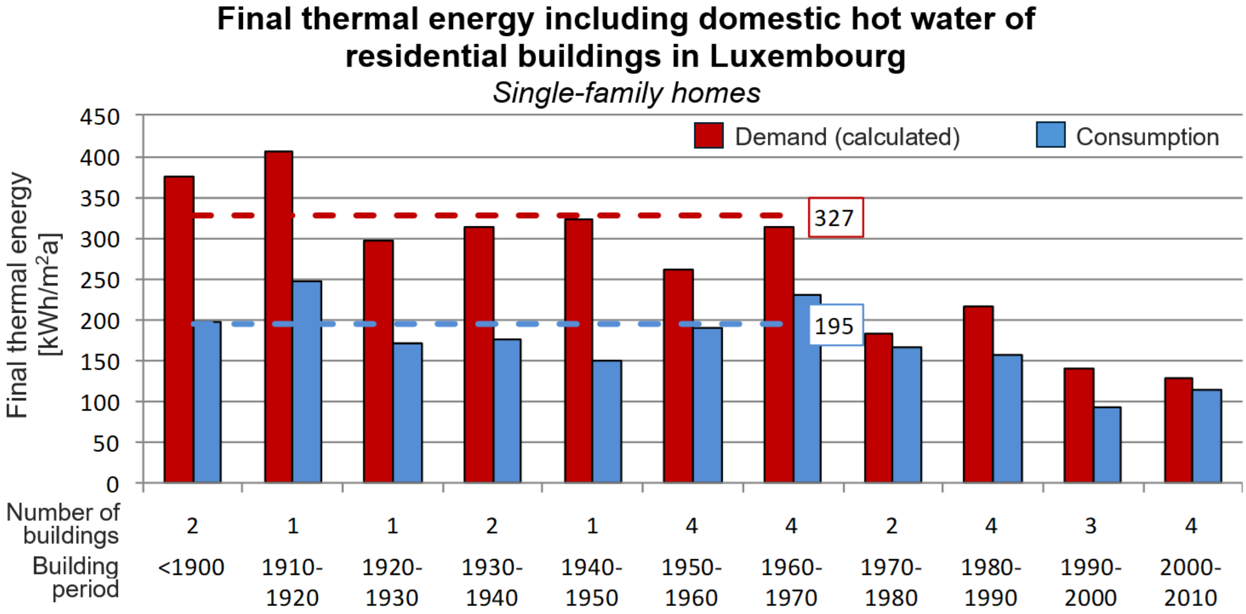


Figure 2.6: Final thermal energy consumption (blue columns) compared to the simulations of the energy certificates (red columns) versus period of construction of 28 single family homes in Luxembourg [25]

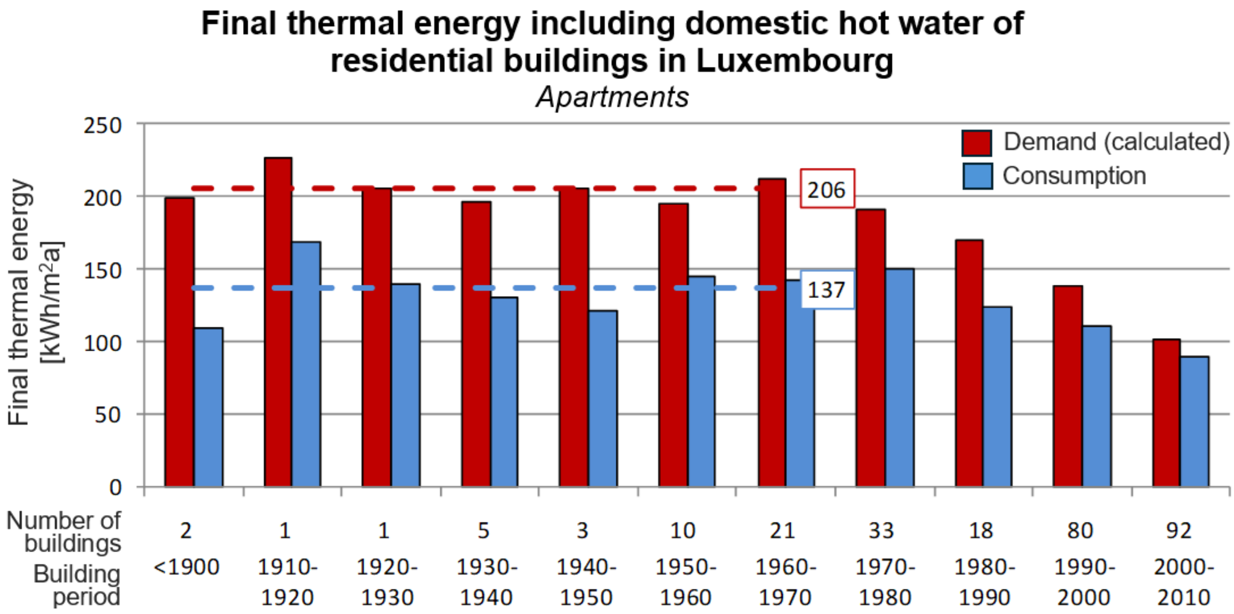


Figure 2.7: Final thermal energy consumption (blue columns) compared to the simulations of the energy certificates (red columns) versus period of construction o 266 appartements in Luxembourg [25]

The same pattern is observed by Merzkirch et al. (2014) and Hoos (2012) on their comparison of real used thermal energy with the simulated values from the energy certificates in Luxembourg [24], [25]. **Figure 2.6** and **Figure 2.7** shows the results from Hoos (2012), for residential buildings separated by single family homes and apartments, respectively. While **Figure 2.8** presents the results from Merzkirch et al. (2014).

The simulations in the energy-certificates overestimate by more than 68% for single-family homes and by 50% for apartments built before 1970. Then, the gap decreases. Hence, no influence can be observed by the year of construction until 1980, as buildings are permanently refurbished and/or operated differently [25][26].

The findings of these two case studies have exposed a substantial discrepancy, between calculated and measured thermal energy requirements of older residential buildings, amounting to a range of up to 75% [24][25].

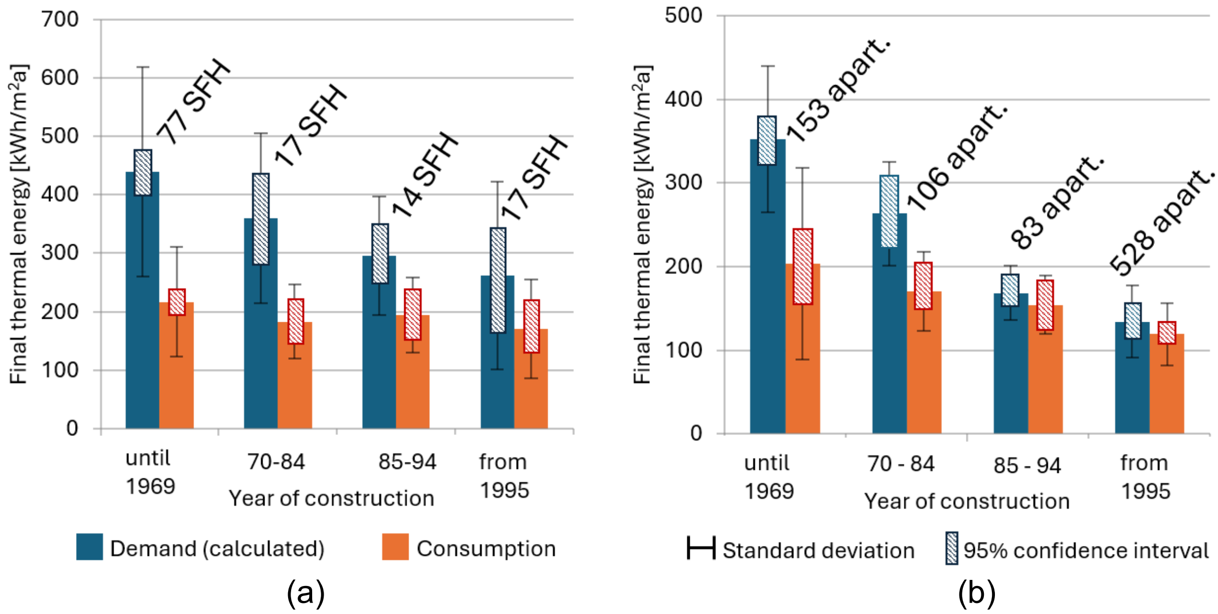


Figure 2.8: Final thermal energy consumption (orange columns) of residential buildings in Luxembourg compared to the simulations of the energy certificates (dark blue columns) versus period of construction, referring to the net floor area, with the interval of standard deviation and the 95% confidence interval for the mean value: (a) 125 single-family homes; (b) 870 apartments [24]

The Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR) compiled the analysis of the prebound effect in non-residential buildings in Germany, showing a performance gap between calculated and measured heat consumption varying from 13% to up to 62%, with an average of 44% lower measured consumption than the calculated, for all study cases [26]. Furthermore, literature review regarding the performance gap in non-residential buildings shows an average gap of 67% from the analysis of 11 school buildings, while the analysis of 3 universities presented an energy performance gap of 62% [6].

A report from the Umwelt Bundesamt states that the overestimation of demand increases with decreasing thermal protection, as previously showed, and assuming that the valid calculation methods are generally correct, it reinforces that the possible source of discrepancy remains the boundary conditions and discusses standard values recommended by norms regarding energy efficiency assessments. It discusses that in buildings with high thermal losses, indoor temperatures would set to 18°C instead of the recommended 20°C for residential buildings following the DIN V 18599-10, leading to lower measured consumptions than calculated. It also indicates that the DIN V 18599 air exchange rate values between 0.6 1/h to 0.8 1/h would be too high for winter period, proposing the adoption of 0.24 1/h instead for areas only ventilated by windows, as a more realistic rate [27]. Furthermore, in the residential sector the prebound effect is correlated to behavioural adaptation, where occupants may use less energy than expected due to cost concerns, or unheated spaces, leading to an overestimation of the savings potential of retrofits [28][29].

2.2.2. Energy renovated buildings

Reaching a realistic calculation of energy consumption of a building is crucial to quantify the energy savings from retrofitting measures, and it is essential for planning the energy transition in the building sector. Therefore, when assessing energy efficiency renovations, the rebound effect must also be considered, to avoid big gaps between anticipated and actual savings. The rebound effect describes situations where energy efficiency improvements result in lower operational costs, which can lead to increased energy consumption due to changes in occupant behaviour, partially offsetting the expected savings [30].

As presented in the GAPxPLORE study, the pre-bound effect is more expressive than the performance gap after retrofit, however, the rebound effect is observed, with higher measured consumption than simulated [12].

The performance gap after retrofitting might be caused by two main factors: changes in the execution and occupant behaviour, with new operational setting and the addition of new appliances to the building. During the construction phase, a significant portion of a building project can change due to various factors, including design adjustments to technical restrictions, material availability, labour challenges and safety concerns. Unforeseen site conditions, design conflicts, or changes in building regulations may require modifications, while material shortages can lead to substitutions. The extent of changes typically varies from 5% to 25%, leading to real conditions significantly different than the initially proposed [27][31][32][33].

Regarding the occupant behaviour Jacopo et al. (2023) observed a rise in indoor temperature values following renovations [32]. In a similar direction, the Umwelt Bundesamt (2022) recommended increasing the reference indoor temperature to 22 °C, in line with DIN EN 15251, to improve the accuracy of demand calculations [27].

In the study on deep energy renovations in Ireland, Hassan et al. (2024) evaluated the trade-offs between operational energy savings and indoor air quality, revealing that while renovations improve thermal comfort, it may increase concentrations of indoor pollutants due to inadequate ventilation systems and new materials used [34]. Hoos (2012) also emphasised the effect of the variation in the air change rate on the energy gap after refurbishment in Luxembourg. This study established that the implementation of measures to improve the airtightness of the building resulted, in some cases, in a higher energy consumption. This fact was related to the increment of air exchange rates, with residents opening more often the windows to avoid problems such as mould growth [25]. Jacopo et al. (2023) observed the same behaviour, from the analysis of the indoor air before and after retrofits [32].

Literature review highlights the need for a thorough verification during the execution of renovations, combined with information regarding the impact of operation. Furthermore, the adoption of monitoring practices can also contribute to a more efficient operation. The effectiveness of advanced monitoring and energy management systems has been highlighted in various studies. According to Techem (2023), conventional residential heating systems can achieve efficiency gains of up to 15% when equipped with improved monitoring technologies [35]. Moreover, implementing individual energy metering and billing has been associated with an average decrease of around 20% in final energy consumption [36], emphasizing the critical role of occupant engagement in managing energy use.

2.2.3. New buildings

New buildings present an expressive energy performance gap, where the predictions normally show lower demands than what is actually measured during the first years of operation. A review from Zheng et al. (2024) regarding the energy performance gap between simulated and measured values, attributes these effects to overestimations of energy efficiency in the project stage, or during simulations. During the course of the project, a number of issues were identified, including incompatible design, a poor level of detail, inadequate construction and inappropriate operation. The deviations concerning the simulation phase include the use of generalised meteorological data, inaccurate physical parameters, such as thermal transmittance, infiltration rates and thermal bridges, simplification of models. Occupant behaviours, such as schedules, temperature settings, and ventilation rates, which do not reflect the reality, also leads to discrepant results [22]. These observations emphasize the importance of accounting for the existing energy performance gap when planning the replacement of buildings, to ensure that predicted savings and efficiency measures reflect realistic operational conditions.

2.2.4. Gap in the operational energy use

A significant portion of the energy performance gap is attributed to the operation of buildings. Independently of the type of building, a significant portion of the deviation is attributed to user behaviour and technical set-points. In their study concerning occupant behaviour, Jia et al., (2017) states the contribution of users in the energy performance gap [37]. Salvia et al. (2020), showed in their study of retrofitted buildings in Milan, that part of the energy performance gap is related to a lack of knowledge concerning the operation of technical installations after retrofitting, but also pre-established concepts of comfort. It stresses the importance to inform and train users, integrating them in the goal to achieve impactful results from energy-saving measures [38].

Recent analyses have addressed the problem of mismatch in the energy consumption, where automatic system settings are predetermined but do not correspond to actual usage patterns. Data mining techniques have been applied to detect these inefficiencies and highlight potential energy savings. In one study focusing on office buildings in Germany, it was observed that lighting systems remained active continuously, despite occupancy fluctuating by as much as 60% during working hours [39]. Likewise, research in residential buildings uncovered inconsistencies between energy use and occupancy patterns, suggesting that behavioural interventions could yield significant reductions in wasted energy [40].

In a revision of more than 100 publications concerning the impact of occupant behaviour in energy performance gap in building operation, Delzendeh et al., (2017) highlights the challenge for simulations, due to the complex and dynamic nature of occupant behaviour. It also states that around 75% of the studies in the topic focus in residential and office building [41]. The review from Zang et al., (2018) also present an impact between 10% to 25% for residential buildings, and 5% to 30% for commercial buildings, in energy-saving related to the building operation [42].

Research on non-residential buildings in Singapore highlights the crucial role of facility managers in overseeing and maintaining technical systems. The study demonstrated that proactive and effective management practices can lead to a 36% improvement in energy performance [43].

2.2.5. Sufficiency

The concept of sufficiency involves limiting resource use to maintain an acceptable standard of operation. In the context of building energy savings, a systematic review highlights that adjusting operations in areas with varying occupancy can significantly reduce energy consumption while still meeting the specific operational requirements of each activity [44]. According to the IPCC, sufficiency measures in Europe and Eurasia have the potential to achieve carbon savings of up to 15% [45].

A study concerning the barriers to achieve impactful results from energy saving-measures defines the concept of induction effect, exploring the influence of the technological advances, and the constant need for additional products and appliances, stating that smart home users, on average, own eight additional smart devices, increasing overall energy consumption [46]. This confirms the results from a review concerning rebound effect, which states that although people can have a significant impact in reducing carbon emissions, this is only possible with consistent actions in different domains [47].

2.3. Renewable energies in the building sector

The building sector is a major contributor to global carbon emissions, primarily due to its high demand for electricity and heating. Enhancing energy efficiency and integrating renewable energy sources are therefore critical strategies for reducing the sector’s carbon footprint. Despite ambitious climate targets, progress in the building sector remains limited compared to the energy sector, where several European countries, have advanced electrification efforts to decarbonise their economies.

However, the integration of variable renewable energy sources, such as solar and wind, presents new challenges. Their intermittent nature requires additional balancing power, and without sufficient storage, electricity supply often fails to match demand, leading to curtailment, highlighting the need for stronger grid infrastructure and large-scale, non-fossil energy storage solutions. Initiatives like the MosaHYc hydrogen pipeline in the Greater Region demonstrate the potential of green hydrogen as a storage medium, but also the complexity and cost associated with flexible balancing solutions, even when leveraging standby coal power plants or highly efficient gas-steam facilities.

These challenges indicate that electrification and renewable integration, while essential, are constrained by infrastructure, intermittency, and economic considerations. Alternative strategies, including renewable fuels such as green hydrogen derivatives or Hydrotreated Vegetable Oil (HVO), may be necessary in cases where electrification is impractical, particularly in the case of older buildings such as the subject of this analysis.

This section focuses on the role of renewable energy systems in the building sector, examining the potential of photovoltaic systems, hydrogenated vegetable oil and hydrogen, to reduce carbon emissions, support climate targets, and enhance energy independence while contributing to long-term economic benefits.

2.3.1. Photovoltaic systems

Photovoltaic systems in buildings displace electricity that would otherwise be sourced from the grid, which may still include a significant proportion of fossil fuel generation. The Energy Performance of Buildings Directive (EPBD) revision further accelerates the deployment of photovoltaics through provisions requiring new buildings to be "solar-ready" and, in many cases, to include on-site solar installations.

In Europe, the integration of photovoltaics into the electricity mix has already translated into measurable carbon savings in the building sector. The carbon intensity of residential electricity use decreased significantly, with the average European electricity mix emission factor dropping from 396 gCO_2/kWh in 2000 to 270 gCO_2/kWh in 2021. This shift, largely driven by the rapid growth of renewables such as photovoltaics, enabled consistent emission reductions across building end-uses. These results demonstrate the pivotal role of photovoltaics in reducing the carbon emissions in buildings and contributing to the European climate neutrality goals [48].

The cost of photovoltaic systems has declined by over 80% in the past decade, making rooftop solar economically viable in of Europe [49]. Feed-in tariffs, net-metering schemes, and building-integrated incentives have facilitated adoption. Moreover, innovations in smart inverters, energy storage, and digital energy management systems enables self-consumption and grid interaction.

Photovoltaics have become a cornerstone of the energy transition in the European building sector. Their rapid deployment is contributing meaningfully to the reduction of operational carbon emissions, aligning with EU climate goals. While technical, regulatory, and social challenges remain, the scaling up building-integrated photovoltaics will be essential in achieving a sustainable, resilient, and carbon-neutral Europe.

2.3.2. Hydrogenated vegetable oil

Hydrogenated Vegetable Oil (HVO) is produced in industrial scale, by the hydrogenation and hydrocracking of vegetable oils and animal fats, from 1st or 2nd generation, using hydrogen and catalysts, at high temperatures (between 350 – 450°C) and pressures (4-15 MPa) [50]. The triglycerides and fat acids pass through a hydrotreatment to remove oxygen, producing a hydrocarbon chain ($C_n – H_{2n+2}$) with varying properties and molecular size depending on the feedstock characteristics and the process conditions [51][52]. The similarity with fossil fuels allows the transition to lower emission solutions, while profiting from existing infrastructure [53].

The HVO has similar properties to the conventional heating oil allowing direct application in oil boilers, representing an opportunity to replace fossil fuels, with extensive documentation focussed on existing internal combustion engines [50][54][55][56]. In the context of research, the utilisation of this fuel in the heating of boilers is still not broadly explored. However, field trials and practical applications are being realised through the blending of the fuel with other substances, and its replacement in full. Both, fuel providers and boiler manufactures attest the possibility to fully replace the heating oil by HVO, with minor changes.

In terms of carbon emission savings during the operation of the system, it refers to the difference between the carbon emissions from the heating oil, and the HVO, and for the former to be recognised as renewable fuel under the Renewable Energy Directive (RED III). The carbon emissions of the HVO vary enormously with regards to the type of raw material used in the process. Typical emission values according to the production pathway determined in the directive, shows a variation from 11.9 g CO_2eq/MJ for waste cooking oil, to 45.8 g CO_2eq/MJ, for oil from rapeseed. HVO used to produce heat needs to meet the greenhouse gas (GHG) emissions savings thresholds, considering the reference of 94 g CO_2eq/MJ. The thresholds in question refer to the year of the production plant installation, varying from 50% of the reference for plants commissioned prior to 2021, and 70% of the reference for plants commissioned from 2023 onwards. This means that the new plants cannot use rapeseed oil in the feeding stock [57].

To be eligible as renewable fuel according to the RED III, it also has to be compliant with the low indirect land-use change feedstock risk, which excludes palm oil [58]. Further restrictions concerning the ban of feedstock related to deforestation is observed in the national levels, in France and Germany.

Regulatory frameworks exist to support the effective adoption of hydrogenated vegetable oil as a decarbonisation measure in heating systems. However, careful attention is required during the procurement process to ensure that the compliance, verifying the origin of the product and its feedstock, and that all relevant regulations are fully respected.

2.3.3. Hydrogen

According to literature review of De Masi et al. (2024), the integration of hydrogen technologies in the building sector demonstrates clear potential from both energy and environmental perspectives, yet widespread adoption remains constrained by high implementation costs and system complexity of fuel cells. Current research often relies on laboratory-scale prototypes, which may not accurately reflect in-field performance, highlighting the need for experimental data under realistic operational conditions. Notably, the use of solid oxide fuel cells in micro-combined heat and power units offers higher electrical efficiency compared to conventional cogeneration systems and presents a promising pathway for nearly zero-energy buildings (nZEBs). These findings support the feasibility of transitioning from nZEBs to hydrogen-based zero-emission buildings, providing valuable insights for designers and practitioners seeking cost-effective and practical hydrogen integration strategies [59].

Ribeiro et al. (2025) explore the adoption of hydrogen in combined heat and power engines for district heating systems, demonstrating technical feasibility but highlighting significant economic challenges, primarily due to the high costs of hydrogen [60]. These economic barriers, however, are expected to decrease in the coming years as European initiatives, such as the development of the hydrogen framework and supportive policies to promote technological advancement, scale-up of production, and market integration.

The European Commission is intensively working on the Clean Industrial Deal, focussing on decarbonisation and competitiveness. It proposes to launch the Industrial Decarbonisation Accelerator Act, to speed up related planning, tendering and permitting processes. Besides, it focuses on reducing energy costs, while including hydrogen and critical raw materials in the AggregateEU from the EU Energy Platform. This mechanism of demand aggregation and joint purchase, is created to contribute to ensure the security of gas supply.

Since the launching of the European Hydrogen Strategy the regulatory framework regarding hydrogen is evolving. The target of reaching an electrolyser installed capacity of 40 GW and the production of 10 Mt of domestic renewable hydrogen production, is reiterated by the RePower EU, which also foresees the imports of 10 Mt by 2030 [61]. Furthermore, the Renewable Energy Directive RED III establishes that hydrogen should represent at least 42% and 60%, by 2030 and 2035 respectively, of the renewable fuel of non-biological origin share used by industry [58].

The Important Projects of Common EU Interest (IPCEI) also play an important role in the development of the hydrogen supply chain. This status provides projects with simplified state aid approval, political and administrative support, and network across the borders.

The creation of the European Hydrogen Bank contributes to ramping up the production of renewable hydrogen [62]. The first subsidy auction happened in the first semester of 2024, with winning bids premium between 0.37 €/kg and 0.48 €/kg, and a total funding of 720 million € dedicated for the production on 1,52 Mt of renewable hydrogen. In December 2024, a 1,2 billion € second round was launched with a ceiling premium price of 4.0 €/kg, which is 0.5 €/kg of hydrogen lower than the first round. The awarded projects requested a premium ranging from 0.2 €/kg to 0.6 €/kg of hydrogen. Most project promoters applied for support below 0.5 €/kg, consistent with the results observed in the first auction. Geographically, the majority of awarded projects are located in Spain (8), followed by Germany (2), the Netherlands (1), and Finland (1), with the largest-scale projects situated in Germany and the Netherlands [63].

As part of the European hydrogen and gas decarbonisation package, the new Directives 2024/1788 and 2024/1789, aim to establish common rules for the internal markets for renewable gas, natural gas, and hydrogen, while speeding up the response to injection requests. The proposal outlines the creation of a new autonomous entity, the European Network of Network Operators for Hydrogen (ENNOH), with the mandate of overseeing the planning, development, and operation of the EU hydrogen infrastructure.

The Luxemburgish hydrogen strategy released in 2021, focussed on the hard to abate sectors, starting by replacing the current demand by renewable hydrogen, followed by its adoptions in certain industrial procedures [64]. The strategy is currently under revision with an update foreseen for 2025. Furthermore, the updated National Energy and Climate Plans (NECP), from July 2024, reinforces the role of hydrogen, the need for pilot projects, the cooperation with neighbouring countries and the prospect to have the first hydrogen pipelines by 2035.

The development of the Luxembourgish hydrogen framework counts with local trimestral “Taskforce H_2 Luxembourg” bringing together the main players in the country [64]. A five year long hydrogen valley project funded by the Horizon Europe Programme, called LuxHyVal is being developed to replace the national current fossil-based hydrogen demand. Moreover, the Ministry of Economy launched in October 2024, a 110 million € call for demonstration projects for the production of renewable hydrogen [65].

Regarding the development of the infrastructure in Luxembourg, while a draft law project regarding the hydrogen transport network, Creos has joined the HY4Link project to foster decentralised green hydrogen production across the Greater Region by providing the necessary hydrogen transport infrastructure. The project aims for a cross-border connection, where the first part, planned for 2030, is a connection between a production site in Thionville in France, and Frisange in Luxembourg, to be connected to the industrial zone in the south of the country [66].

The first part of the HY4Link project also includes the possibility to connect to the mosaHYc project, at Bouzonville [66]. The mosaHYc project is a cooperation between the distribution network operators Creos (Germany), NaTran (France), and Encevo (Luxembourg), for repurposing 70 km of existing gas pipelines and building further 20 km new hydrogen pipelines, to connect producers and users in the Greater Region. The pipeline is planned to be commissioned ~~in~~ at the end of 2028, with a maximum capacity of 5.5 GWh/day [67].

The second part of the HY4Link project, expected for 2034, refers to the interconnections with the European Hydrogen Backbone [66]. The European Hydrogen Backbone is an initiative for establishing hydrogen supply corridors in Europe. The road map published in November 2023, shows 40 concrete projects representing 31,500 km of hydrogen pipelines to be commissioned by 2030. The report also includes the results of a study comparing a clustered hydrogen ecosystem with an interconnected one, showing savings of 330 billion €, between 2023 and 2050, for the integrated approach in Europe [68].

Figure 2.9: mosaHYc project [67]

The HY4Link interconnections to the European Hydrogen Backbone, guarantee the inclusion of the Greater Region into green hydrogen supply network. The connection at Nancy (FR) reaches the south of the country and the Corridor B – Southwest Europe and

North Africa, while at Bras (BE) it reaches the Corridor C – North Sea, and it also ensures access to the import hubs in Antwerp, Zeebrugge, Rotterdam, and Dunkirk [69].

The process that involves feasibility studies authorisations, permitting, contracts and market commitment, until the final investment decision and the construction phase starts, is estimated to take around 7 years until the commissioning of the hydrogen pipelines [68]. Therefore, the technical feasibility studies regarding the local connections from Frisange have already started, assuming different demand scenarios. Risk management mechanisms are also being developed, to reduce the uncertainties regarding the transition.

Figure 2.10: HY4Link [70]

In summary, while hydrogen remains an emerging player in the Luxembourgish energy landscape, recent establish the foundations for a sustainable and integrated ecosystem, with strategic partnerships, pilot projects, and national policy alignment with EU directives.

These advancements are indicative of not only technological and infrastructural progress, but also a growing political and societal commitment to decarbonisation. Despite the challenges that still lie ahead, the ongoing developments in Luxembourg indicate that hydrogen could play a significant role in the transition towards a low-carbon future.

2.4. Energy consumption in educational buildings

Energy consumption in school buildings has been a growing concern over the past decades, particularly in Europe, where there is an important existing building stock. School buildings are significant consumers of both electrical and thermal energy, driven by the need for lighting, heating, cooling, ventilation, and the increasing use of information and communication technologies in education. Understanding the evolution of energy consumption patterns and key influencing factors is essential for optimizing energy efficiency and reducing carbon footprints in these institutions.

2.4.1. Evolution over the years

Energy consumption in school buildings has undergone significant changes over the past decades due to shifts in architectural design, construction materials, heating and cooling technologies, and user behaviour. A study concerning the energy consumption of 74 schools and 13 universities built between 1950 and 2000 in Finland, shows that the final heating consumption tend to reduce over the years. As shown in **Figure 2.11** and **Figure 2.12**, concerning school and universities separately, a reduction of 16% of heating consumption between the older buildings and those built after 1980s, and a further reduction of 22% when compared to those built after 2004. However, there is a slight increase on the electricity consumption of schools, while it tended to decrease at the universities [71]. This tendency is also confirmed by Thewes (2011), in his analysis of the electricity consumption of 68 schools in Luxembourg, built between 1994 and 2008. Thewes also shows an increase from ~20 kWh/m^{2}a to ~40 kWh/m^{2}a with a standard variation of ±15 kWh/m^{2}a, which is ±47% with respect to the mean average of 32 kWh/m^{2}a [72].

School buildings constructed before the mid-20th century were designed primarily for natural ventilation and daylighting, relying on large windows, high ceilings, and masonry walls to regulate indoor temperature. These buildings had minimal mechanical heating and no air conditioning systems, leading to relatively low energy consumption but significant thermal discomfort during extreme weather conditions [73].

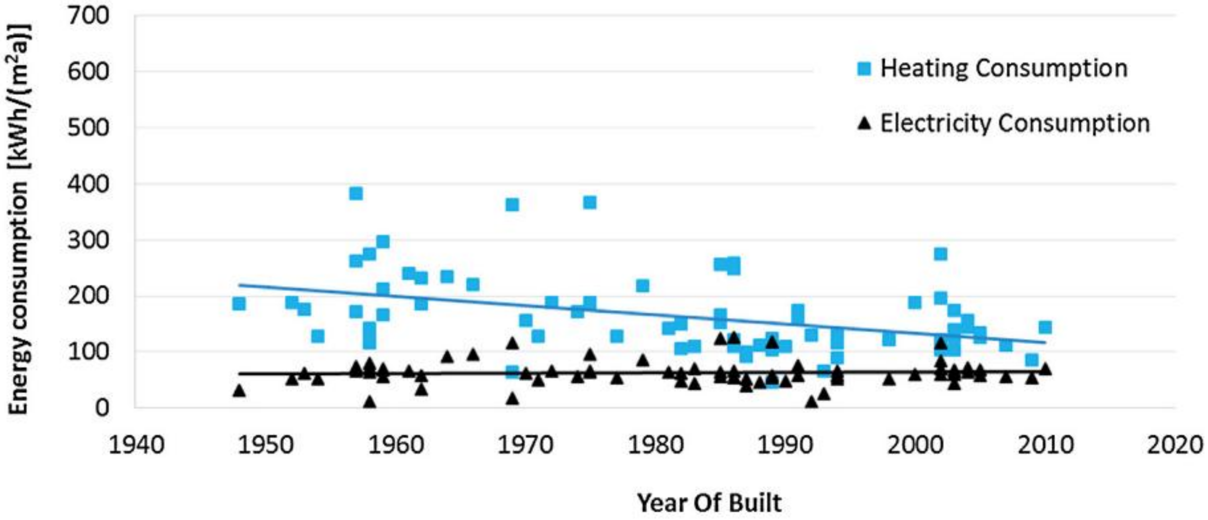


Figure 2.11: Heating and electricity consumption in the studied schools in the City of Espoo [71]

After 1950 Europe saw a massive expansion of school infrastructure. Schools built during this period prioritised functionality and cost-effectiveness over energy efficiency. Concrete, steel, and single-pane glass windows became common, leading to high heat losses and poor insulation [73].

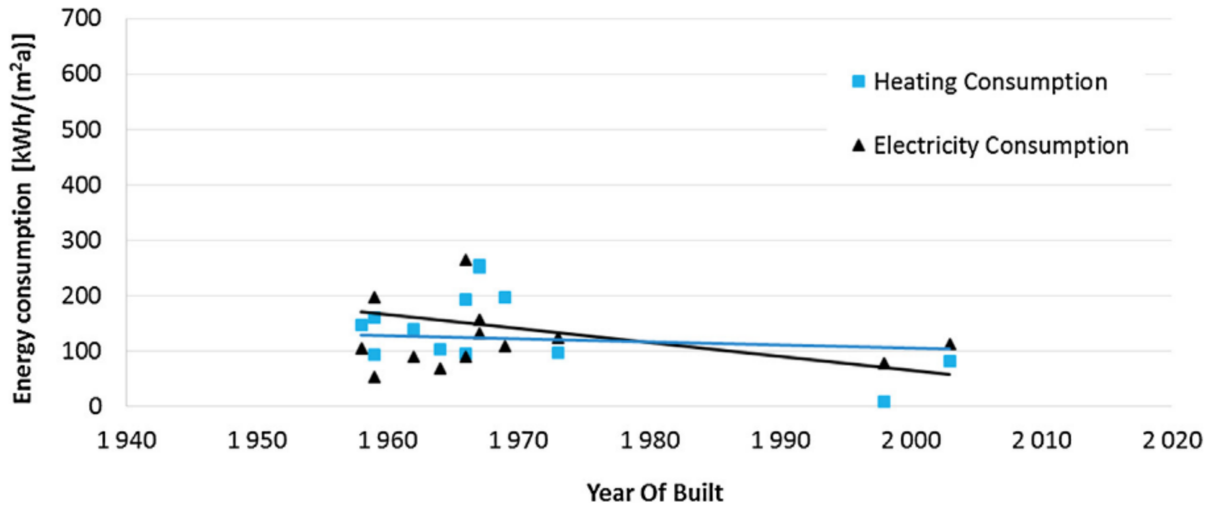


Figure 2.12: Heating and electricity consumption in the studied universities in the City of Espoo [71]

In the 1970s, the energy crisis pushed the governments to rethink energy use in public buildings. At this moment, many European countries started to introduce basic energy efficiency measures, including improving thermal insulation and tightness, adopting double-glazed windows and adding basic heating controls such as thermostats. The first energy efficiency directives started in the 1990s, increasing the restrictions regarding thermal losses in the buildings and efficiencies of technical installations.

In the latest years, a reduction in thermal consumption in observed in **Figure 2.11**. This tendency is due to the increasing insulation of buildings, but also to the systematic adoption of heat pumps to replace boilers, shifting the consumption towards electricity. Although the efficiency of lighting systems has improved over the years, the adoption of oversized illuminance rates is also frequent. Moreover, the increasing number of computers, servers, projectors, printers and connectivity devices are being installed in educational buildings, prevent the further reduction in electricity consumption.

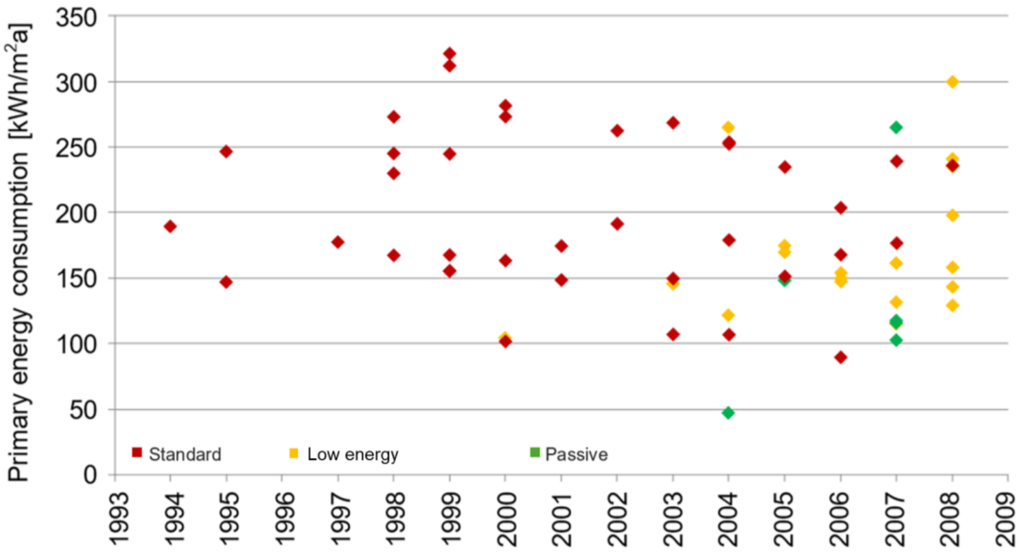


Figure 2.13: Primary energy consumption schools in Luxembourg for 3 categories ('passive', 'low-energy', 'standard') versus year of construction [72]

Furthermore, in his analysis of school buildings in Luxembourg, Thewes (2011) demonstrates that no correlation can be established between neither the year of construction, nor the building energy performance categories, and the primary energy consumption (considering the Luxembourgish primary energy factors at the time, of 1.1 for gas and 2.66 for electricity), as previously observed for residential buildings. Although, in average the low energy and the passive buildings show reductions of 16% and 35% with regards to the standard buildings. **Figure 2.13** shows that there is no clear decreasing tendency, with important variations in energy consumption within each class [72].

2.4.2. Benchmarks in educational buildings

Energy benchmarks are reference values used to evaluate the energy performance of buildings, comparing actual energy consumption against typical values for similar buildings. They help to identify inefficient operations which require energy-saving interventions, and to set realistic reduction targets.

In energy efficiency of buildings, benchmarks typically assess total energy consumption divided per the gross floor area, although variations are observed methodological and country wise. Luxembourg, for example, adopts the conditioned area of the net surface inside the envelope, as the reference area to evaluate energy efficiency [74].

School buildings are unique in their energy consumption patterns due to specific operational schedules, occupancy levels, and functional requirements. The main energy consumers in these buildings include heating systems, lighting, information and communication technology equipment, cooling and ventilation systems, and other miscellaneous uses such as kitchen and swimming facilities.

Energy consumption in educational buildings presents important variations depending on the disciplines [75]. Khoshbakht et al. (2018) showed that buildings used for research are more energy-intensive than academic offices [76].

Energy consumption in European school buildings

Table 2.1: Energy annual consumption in older secondary schools excluding swimming pools (based on [25][77])

Country	Thermal energy [kWh/m²a]	Electrical energy [kWh/m²a]
Germany	191	45
Luxembourg	161	35
Northern Ireland	120	16
United Kingdom	144	33

Energy benchmarking methodologies vary between measured, theoretical and regulatory. The measured benchmarks are empirically defined from collection of real energy consumption. The theoretical values are obtained from simulation models, and as previously discussed, may present an important performance gap. Regulatory references, on the other hand, are derived from official energy performance regulations and are used to classify buildings.

A review paper concerning energy consumption in schools, groups many studies in Europe. **Table 2.1** shows the split between typical thermal and electricity specific yearly consumption in Germany, Luxembourg, Northern Ireland, Portugal and United Kingdom, in school buildings.

Usage distribution

An American study on the energy consumption distribution by type of consumer, draw attention to the impact of space heating including hot water [54%], lighting [14%], cooling [10%] and ventilation [9%], representing together 87% of the total energy consumption. In this study, cooking and refrigeration represent together only 3% [77]. At the same time, the analysis of British schools shows a much important demand from heating and hot water [78%], followed by catering [9%] and lighting [8%] [78].

Thewes et al., (2014) show that in Luxembourg, the electricity consumption in school buildings with canteens and sports halls increases on average by 10 kWh/m^2 with regards to the total conditioned surface, when compared to the consumption of buildings without both facilities [79]. The analysis of secondary schools in the United Kingdom shows an average increment of 27 kWh/m^2 in buildings with swimming pools [78].

Local Benchmarks

In Luxembourg, Hoos (2012) established a local reference, as presented in **Table 2.2**, by studying the energy consumption of 29 buildings from the 45 secondary schools in the country, built before the year of 1995 [25].

Table 2.2: Summary of calculated mean values referred to gross floor area (GFA) [25]

References for school buildings	Calculated	Building sample
Mean heated gross area of sample including 95% confidence interval	15.400±4.000 m^2	25
Mean end-energy for electricity	35±16 kWh/m^{2}a	24
Mean end-energy for heat use including hot water of sample including standard deviation	161±71 kWh/m^{2}a	26

According to a literature study developed by Hoos et al., (2016), the final heat energy of schools does not directly correlate with a year of construction due to subsequent partial or full modernisation and renovation activities. Hence, it is proposed to use end energy as a classification parameter, instead of the building age by separating buildings into 3 classes, entitled low, medium and high final heat energy consumption, based on literature review, as presented in **Table 2.3** [80].

Table 2.3: Classification of school building in Luxembourg built before 1995, according to end-energy for heat, including hot water [80]

End-energy including hot water	[kWh/m^{2}a]
Low consumption	≤ 90
Normal consumption	90 - 160
High consumption	≥ 160

These local benchmarks provide a practical framework for evaluating the energy performance of educational buildings in Luxembourg. By focusing on the average consumption of electricity and final heat energy, rather than the year of construction, the classification method enables more accurate comparisons and can inform targeted energy efficiency strategies within the educational sector.

2.4.3. Performance gap in educational buildings

The energy performance gap, concerning the difference between simulated and measured consumption values is also observed in school buildings. Studies showed a higher energy performance gap in educational buildings than in other building types [81][82]. Zheng et al., (2024) identified gap ratios ranging between 0.5 to 4 for educational and research buildings [22]. While a study concerning the energy performance gap in low-energy schools in Sweden showed a deviation varying between -44% to +28%, observing the important impact of the ventilation rates and operational times and heating [83].

Concerning the mismatch between demand and energy consumption the analysis of consumption patterns in educational buildings shows that 48% of total yearly energy consumption happened during vacant periods [84]. A study by Dronkelaar et al. (2019) investigated the causes of the performance gap in universities and office buildings. It highlights the significant impact of vacant periods and equipment power density. To a lesser extent, material properties, system efficiencies, and air tightness also contribute to the gap [85]. A potential to save up to 70% of the energy used for lighting systems is identified, just by adapting the operation to the real requirement [86]. Furthermore, the optimisation of activity schedules at a university in Xi'an showed the potential of 3.6% reduction in total energy consumption and 6.71% in lighting energy [87].

2.4.4. Behavioural impact

Energy-saving interventions in educational buildings are most effective when technical solutions are combined with behavioural strategies. According to De Leeuw et al. (2015), initiatives that focus on enhancing perceived control of students tend to be more successful among high-school students than those that simply highlight positive outcomes. The study also indicates that descriptive norms, such as the environmentally friendly actions modelled by parents, family members, and other influential figures, exert a stronger influence than injunctive norms, which are based on what others say should be done. Building on these findings, norm-based interventions in schools may be more effective when they actively involve families and communities in modelling sustainable practices [88]. Cincera and Krajhanzl (2013) further emphasise that pupils are more likely to engage in pro-environmental behaviours when they perceive themselves as participants in the decision-making process [89]. This insight is reinforced by more recent initiatives, such as the ENERGE project, which demonstrated that creating school-based committees and teacher networks can act as powerful drivers of change [90]. By involving students directly in energy-related decisions, monitoring, and interventions, these committees not only encouraged behavioural change but also established a culture of reciprocity and collaboration within schools. The project further showed that when pupils see their actions contributing to tangible improvements in energy efficiency, their motivation and long-term engagement in sustainability practices increase significantly [91].

2.5. Summary and research gap

Despite the urgency of climate targets, the building sector continues to struggle with decarbonisation, constrained both by the slow transformation of existing stock and by the limited impact of many implemented measures. The German energy report from 2024, shows only minor reductions in greenhouse gas emissions from buildings, primarily due to decreased heating demand from warmer weather, while overall emissions remain above legislative targets [92].

Literature reinforces that the challenge is not merely the slow rate of renovation, but also the limited net impact that renovation can achieve once embodied energy is considered. El Hajoui (2025), present an literature review showing that the total embodied energy, associated with stages A1, A4, and C1 (**Figure 2.1**), typically lies within 2000 ± 1000 kWh/m^2, although even larger variations are reported [97][98][99]. **Figure 2.4**, **Figure 2.6**, **Figure 2.8**, and **Figure 2.13** further illustrate that there is no clear distinction in the energy characteristics of older versus newer buildings. Instead, the notable difference emerges between energy-efficient and low performing buildings, with only a weak correlation to age. This observation helps to explain why the building sector continues to struggle with meeting its climate targets, as the debate tends to focus solely on renovation rates, which ultimately only marginally improve overall energy consumption.

Figure 2.4, **Figure 2.6**, **Figure 2.8**, and **Figure 2.13** also show that savings of around 100 kWh/m^2 through renovation or refurbishment can already be considered a good outcome. This leads to the conclusion that the average time to compensate for the added embodied energy of 2000 ± 1000 kWh/m^2 is approximately 20 ± 10 years. In favourable cases, this period may be closer to 10 years, while in unfavourable ones, the embodied energy may not be fully compensated. This conclusion underscores the importance of targeted and carefully selected renovation measures, supported by a thorough, object-specific analysis. Such an assessment must consider a broad range of criteria, including both energy and comfort. It is equally evident that small-scale refurbishment measures can have a substantial impact and should therefore be thoroughly examined before decisions on demolition and rebuilding are made. This is precisely the aim of this dissertation: to investigate selected examples of smaller renovation interventions that also enhance user comfort.

Educational buildings constructed before the introduction of efficiency standards, facing uncertain long-term use, illustrate this challenge clearly. As public buildings involving multiple stakeholder groups, they encounter barriers not only to the implementation of interventions but also to the long-term maintenance of strategies. Addressing these barriers requires decision-making indicators that help stakeholders prioritise interventions, balancing life-cycle effectiveness with economic feasibility, and comfort.

The research from Kaczmarek (2025) has highlighted the persistent challenges in improving the energy performance of educational buildings. A systematic review of interventions in schools across Europe confirms that while technical measures, such as insulation, technical installation upgrades, and integration of renewable energy, are the most frequently applied strategies, they alone are insufficient to deliver the expected performance improvements. A consistent gap remains between predicted and measured energy and carbon savings, driven by factors such as user behaviour, inadequate commissioning, and limited monitoring after implementation. Moreover, the fragmented nature of case studies, often highly context-specific, poses challenges to the replication of research findings on a large scale. The review also stresses that most studies prioritise energy or payback assessments, with limited consideration of life-cycle carbon or integrated decision-making tools. Behavioural interventions, including user awareness campaigns and engagement programmes, are increasingly recognised as essential complements to technical retrofits, both to improve outcomes and to ensure the persistence of savings [93].

National evidence from Germany further supports this perspective. The REGENA project (2016) demonstrated that effective retrofitting of school buildings requires a holistic concept that links technical improvements, such as building envelope upgrades, technical installation optimisation, and lighting retrofits, with behavioural measures engaging teachers, pupils, and facility managers. The project confirmed that calculated and actual savings often diverge, reinforcing the need for continuous monitoring and operational feedback to narrow the performance gap. The active involvement of school communities was found to be decisive for the success and long-term persistence of interventions. By designing its methodology for replication, the project showed that while interventions must be adapted to local contexts, the combination of technical efficiency, behavioural engagement, and systematic evaluation offers a transferable framework for educational buildings more broadly [94].

Finally, despite the deployment of smart technologies, including predictive demand-side management for heating systems, besides the challenges for implementation in older buildings, the potential savings are often insufficient to incentivise consumers to optimise their installations. Studies by Bechtel (2020) and Rehm (2024) demonstrate that, although parametric simulations and neural-network predictions can optimise heating schedules according to electricity prices and weather conditions, the economic incentives remain limited, and widespread adoption is therefore constrained [95][96].

Taken together, these insights underline the importance of moving beyond isolated technical measures towards integrated approaches that balance efficiency, behaviour, and practical feasibility. Building on this foundation, the present research advances the field by developing a structured four-step methodology that not only combines behavioural engagement, auditing, targeted interventions, and performance evaluation, but also integrates energy, carbon, economic, and comfort assessments. By introducing decision-making tools such as avoided carbon cost indicators, the study aims to improve the implementation rate of interventions while maximising their long-term impact and replicability in educational buildings.

3. Methodology

The present study proposes an energetic and economic assessment of both technical and behavioural interventions aimed at reducing energy consumption and carbon emissions in existing educational buildings in Luxembourg, specifically those built before 1990. This assessment is structured around a four-step framework that involves identifying and engaging stakeholders, conducting an energy audit to detect savings opportunities, defining and implementing tailored measures, and assessing their impact to improve future interventions.

This framework was developed in response to the complex challenges faced by older educational buildings, where low energetic performances are often embedded in both the physical infrastructure and user practices. Traditional technical approaches alone have proven insufficient to achieve long-term reductions in energy use and carbon emissions. Therefore, a combined perspective, integrating behavioural engagement with targeted technical upgrades, was necessary to ensure the effectiveness of interventions. The framework provides a structured, iterative process that bridges the gap between analysis and actions suitable for the complex, dynamic and user-intensive environment of educational facilities.

This framework was developed based on a review of relevant literature and insights gained through direct engagement with existing educational buildings, their stakeholders, and the challenges they face in achieving energy and carbon reduction goals. It was designed to be both flexible and context-specific, allowing for adaptation to the unique characteristics of each building and the behaviours of its users. This grounded and participatory approach ensures that the proposed strategies are not only technically robust, but also aligned with user needs and expectations, and economically feasible.

Each step of the framework relies on specific data collection and analysis procedures, adapted to the objectives and requirements of that phase. This chapter outlines these methodological approaches in detail, explaining how the data were gathered, processed, and interpreted to support the development and application of the framework, and to guide the definition, implementation, and evaluation of intervention strategies.

3.1. Framework

This study proposes a four-step framework for reducing energy consumption and related carbon emissions in educational buildings, as illustrated in **Figure 3.1**, based on the concepts of the ENERGE Project, and presented by Delmonte et al. (2024) [99]. These steps integrate technical and behavioural approaches to identify energy-saving opportunities by optimising the operation of technical installations, improving the building thermal performance and integrating renewables.

The proposed steps are designed to be sequential yet iterative, with each step building on the previous one. The activities from preceding stages are not concluded at the initiation of the subsequent stage. Instead, they continue to happen contributing to the subsequent stages. The fourth phase involves the evaluation of interventions and the promotion of continuous improvement through the process of revisiting all previous steps when necessary.

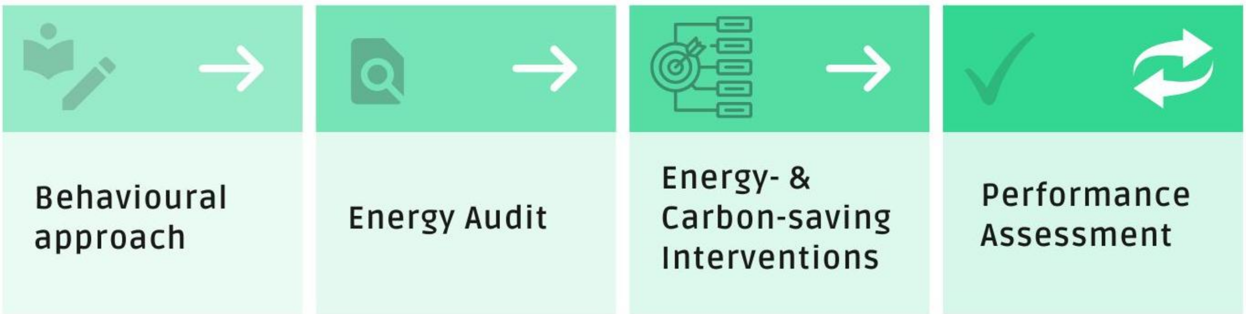


Figure 3.1: Four-step framework for reducing energy consumption and carbon emissions in post-primary educational buildings based on [99]

This structured and iterative approach ensures that energy efficiency efforts in educational buildings are practical, scalable, and sustainable. Through a combination of behavioural engagement, technical assessment, targeted interventions, and continuous monitoring, the framework facilitates a comprehensive and impactful carbon reduction strategy.

Step 1 – Behavioural approach

The first step in the framework addresses the behavioural aspects of energy consumption, recognising that user engagement plays a fundamental role in the effectiveness of energy-saving measures. The process begins with the identification of key stakeholders, including students, teaching staff, facility managers, and administrative personnel, alongside an evaluation of their levels of knowledge, willingness to participate, and access to relevant resources. Engaging all relevant parties is essential, with the level of involvement tailored to the specific characteristics and roles of each stakeholder group This step builds on the approach from Doherty et. al (2022) [91].

In addition to stakeholder engagement this step assesses the readiness of the school to adopt pro-environmental behaviours and implement carbon-saving measures. This includes an evaluation of existing sustainability initiatives and explores opportunities to strengthen collective participation in energy efficiency efforts. Given that literature highlights the influence of operational practices and user behaviour on the energy performance of buildings, discussions on perceived comfort and energy sufficiency are also incorporated. By addressing these behavioural dimensions, this phase establishes a foundation for promoting energy-conscious practices across the school.

The integration of behavioural approaches into energy-saving initiatives is intended to enhance the engagement and acceptability of the interventions. Targeted training and awareness programs, such as the use of educational videos aims to engage students and staff by introducing energy-related topics and highlighting their role as active participants in implementing energy-saving measures. Beyond user engagement, it recognises the role of school staff and facility managers in ensuring the efficient operation of technical installations. Moreover, this improves the dissemination and replicability of these measures beyond the context of the educational buildings, by fostering a culture of energy-conscious behaviour.

Step 2 – Energy audit

The second step consists of a comprehensive energy audit aimed at identifying inefficiencies in the energy performance of the analysed educational building. This process involves extensive data collection related to the building envelope, technical installations, and operational patterns. Parameters, including thermal resistances, air infiltration rates, heating, cooling and ventilation system performance, and lighting efficiency, are assessed in detail. In addition to technical data, energy consumption data are analysed, with a particular focus on their usage pattern and their distribution among different functional areas within the school.

A comparative analysis is conducted, during which the actual energy consumption is evaluated against established benchmarks. This process enables the identification of deviations and opportunities for improvement. A comparative analysis is conducted in which the actual energy consumption of the buildings is systematically evaluated against established benchmarks relevant to similar building types and uses. This comparison allows for the identification of significant deviations from expected performance levels, obtained from simulation models, highlighting areas where energy efficiency can be improved. By pinpointing these discrepancies, the analysis provides a foundation for targeted interventions aimed at reducing energy consumption and enhancing overall building performance.

The active involvement of stakeholders in the audit process enhances contextual understanding, and foster a sense of ownership. Those involved are more likely to support initiatives they have contributed to assessing and defining, thereby increasing the acceptability and feasibility of subsequent intervention measures.

Step 3 – Energy- and carbon-saving interventions

Building on the insights gained from the previous steps, this phase focuses on identifying and implementing energy- and carbon-saving interventions adapted to the specific characteristics of the school building. The intervention strategy is developed by considering both technical feasibility and stakeholder acceptance, ensuring that proposed measures align with available resources and operational constraints.

Simulation models provide insights that enable the preliminary assessment of potential interventions before their implementation. By replicating the energy performance and carbon emissions of a building under different scenarios, these models make it possible to evaluate the likely impact of the intervention measures. This approach not only supports the identification of the most effective strategies but also helps optimise resource allocation, ensuring that interventions deliver measurable improvements in efficiency and sustainability.

The intervention strategy is structured around four key priorities. Firstly, operation is optimised by eliminating unnecessary energy consumption, particularly during unoccupied periods. Secondly, optimising operations during occupied periods and introducing minor adjustments to building use. Third, pinpointed refurbishments are introduced, where minor modifications enhance the energy performance of existing systems while minimising embodied energy impacts. Finally, the strategy explores the integration of renewable energy sources, prioritising the replacement of conventional energy vectors with more sustainable alternatives.

By adopting this structured approach, the framework ensures that intervention measures are both practical and scalable, enabling progressive improvements in energy performance without imposing excessive energetic or financial burdens on the school.

Step 4 - Performance assessment

The final phase of the framework is dedicated to evaluating the effectiveness of the implemented carbon-saving measures through continuous monitoring and assessment. This involves defining indicators for quantifying overall energy savings, reduction in carbon emission, analysing the economic impact of the interventions, and ensuring that modifications do not compromise indoor comfort levels. Additionally, this phase recognises the critical role of facility managers, acknowledging their responsibility in maintaining and sustaining energy efficiency measures over time.

Given that building performance is influenced by dynamic use and operational factors, this phase is designed as an ongoing process rather than a one-time assessment. Regular performance evaluations allow for adaptive management, where strategies can be adjusted in response to emerging challenges or changing conditions. This iterative approach ensures that energy efficiency efforts remain relevant and effective in the long term.

Together, these four steps provide a structured pathway for addressing the challenge of reducing energy consumption and carbon emissions in educational buildings, by combining technical and behavioural approaches. In addition to guiding the implementation of targeted interventions, the framework also supports the energetic and economic assessment of their impacts, enabling a comprehensive evaluation of both performance outcomes and cost-effectiveness.

Having outlined each step, the following chapters demonstrate how this framework informs the structure of the thesis and guides the methodological approach. **Chapter 4** elaborates on **Step 1** by identifying the complex stakeholder chain involving educational buildings in Luxembourg, and analysing their role, their openness, and the challenges they face to implement effective interventions. **Chapter 5** addresses **Step 2**, focusing on the analysis of physics characteristics of the buildings, usage patterns and their energy performance, while **Chapter 6** refers to **Step 3**, with presenting the proposed interventions and their impacts. Finally, **Step 4** is presented in **Chapter 7**, providing an overall assessment of the intervention measures in terms of energetic, carbon emissions, economic and comfort aspects, to allow refinement in further implementation.

3.2. Case study overview

The study focuses on four existing post-primary educational buildings in Luxembourg, constructed between the 1950s and 1990s, prior to the implementation of the first energy efficiency directives. These buildings were selected because they represent a significant portion of the national educational building stock, particularly those currently in a state of transition: while heavily used and accommodating a large number of students, they are on hold for major investments pending decisions about their long-term future. Despite their high occupancy and energy demands, these buildings must reduce their carbon emissions without undergoing large-scale renovations, posing a challenge common across many similar facilities.

Table 3.1: Details of the educational buildings

Educational building	Year of construction	Gross floor area [m^2]	Usage types
Building A	1989	22,511	Classrooms, small sports hall and canteen
Building B	1974	31,940	Classrooms, offices, laboratories, and canteen
Building C	1972	21,748	Classrooms, workshops, sports hall with swimming pool, and canteen
Building D	1953	25,232	Classrooms, workshops, sports hall with swimming pool, and canteen

The selected buildings vary in construction period, functional layout, and usage types. Building A is a relatively simple structure with small workshops, a modest sports hall, and a canteen. Building B includes a mix of classrooms, offices, and laboratories. Building C houses extensive technical workshops and a full-size sports hall with an integrated swimming pool. Building D, the most recently extended, contains large welding workshops, a modern canteen and sports hall, and an old small swimming pool. While all four are located in urban areas, Buildings A, B, and D are situated in Luxembourg City, and Building C is located in the northern part of the country.

Despite differences in size, layout, and use, all buildings share key challenges: the need to reduce energy consumption and carbon emissions, maintain acceptable comfort levels for users, and achieve these goals with minimal financial investment. Their floor areas range between 22,000 m^2 and 32,000 m^2, with building heights of up to three floors and varied architectural typologies. In each case, collaboration was established with the administrative, educational and technical staff to support data collection and ensure continuity throughout the research.

3.3. Data collection

This study analyses multiple parameters, requiring the adoption of diverse data collection methods, equipment, and techniques. The following sections provide a detailed description of the methodologies employed to ensure accurate and reliable data acquisition. These methods were selected to support the identification and evaluation of key aspects of the study, including the role and influence of stakeholders, suitable strategies for their involvement, the energy consumption and physical characteristics of the buildings, the perceived comfort of users, and the effectiveness of implemented interventions. Additional details regarding the data collection procedures and instruments used can be found in the **Annex**.

Table 3.2: Types of data collection

Type of data collection	Description	Details	Building
Behavioural survey (**Step 1**)	Pro-environmental behaviour questionnaire	Section 3.3.1 Annex I	Building B
	Buildings managers to implement energy- and carbon-saving interventions measures	Section 3.3.1 Annex II	Building B
Building characteristics and techniques (**Step 2**)	Analysis of architectural plans and project details, and documentation regarding technical installations	Section 3.3.2	Buildings A, B, C and D
Energy consumption (**Step 2**)	Electrical and thermal energy obtained from energy bills, energy management systems and local measurements	Section 3.3.3 Annex III	Buildings A, B, C and D

Table 3.2: Types of data collection

Type of data collection	Description	Details	Building
Building physics (**Step 2**)	Local measurements to evaluate the thermal transmittance of building components	Section 3.3.4 Annex IV	Building B
	Evaluation of the integrity of building components	Section 3.3.4 Annex V	Building B
	Local measurements to evaluate the air tightness of the building	Section 3.3.4 Annex VI	Building B
Numerical simulations (**Step 3**)	Further data collection to support detailed numerical simulations	Sections 3.3.2, 3.3.3 and 3.3.4	Buildings A, B, C and D
Comfort parameters (**Step 4**)	Physical comfort parameters measurements to evaluate conditions before and after interventions	Section 3.3.5 Annex VII	Building B
	Comfort questionnaires to evaluate conditions before and after interventions	Section 3.3.5 Annex VIII	Building B

Table 3.2 provides an overview of the data collection approach used in this study, along with the corresponding procedures applied to each building in the case study.

3.3.1. Behavioural survey

Literature shows the impact of user behaviour in energy consumption in buildings. Thus, this study proposes a questionnaire to assess their pro-environmental behaviour.

The pro-environmental behaviour questionnaire is composed by 13 statements, presented in **Annex I**, is defined based on established questionnaires on the Theory of Planned Behaviour [100]. Participants were asked to respond anonymously, using a 7-point agreement scale, ranging from strongly disagree (1) to strongly agree (7). The first 8 statements aim to evaluate the building users regarding their perception concerning the importance to implement energy- and carbon-saving measures, their perceived impact, their personal investment, and the role of examples. Two statements concerning attitude and the other two on perceived behaviour [101], two statements referring to behavioural intention [102][102], and two statements on perceived norm [103]. The last five statements focus in identifying the perceived barriers to implement interventions, adapted from Horhota (2014) [104].

A second questionnaire containing 4 qualitative questions is established to evaluate the barriers faced by buildings managers to implement energy- and carbon-saving interventions measures, as presented in **Annex II**. Adopting the same approach as for the users, the participation is anonymous, and the questions aim to identify the level of responsibility, the personal and professional priorities, and barriers faced for the implementation of interventions. This survey focusses on assessing the barriers faced by stakeholders involved in the decision-making process regarding the implementation of sustainable interventions.

3.3.2. Building characteristics and techniques

The data collection of building characteristics and techniques focuses on gathering information about the features of the analysed buildings, including architectural plans and project details related to their structure and operation. It also covers technical installations and their operational patterns. Initial information is obtained from stakeholders, while additional details are gathered through on-site technical visits.

3.3.3. Energy consumption

The energy consumption data is divided in two main groups, electrical and thermal energy. They are obtained through various approaches, starting with a simple analysis of energy bills, the collection of monitoring data of the energy provider and local measurements, as presented in **Table 3.3** and **Table 3.4**.

Table 3.3: Details of electricity the data collection

Educational building	Electricity		
	Data source	Interval	Period
A	ABP EMS	15-minute	2017 - 2023
B	ABP EMS	15-minute	2017 - 2023
C	ABP EMS	15-minute	2017 - 2023
D	ABP EMS	15-minute	2017 - 2023

The level of effort required to obtain the data is directly related to their granularity. The obtention of yearly or monthly overall consumption data requires less time and resources than the identification of the hourly consumption of specific activities and technical appliances within a building.

Table 3.4: Details of thermal the data collection

Educational building	Thermal		
	Data source	**Interval**	**Period**
A	ABP EMS	hourly	2017 - 2023
B	Energy bills	monthly	2017 - 2023
C	ABP EMS Local control	daily	2018-2020
D	Local control	monthly	2017-2018 2022-2023

The analysis of the energy bills delivers an overall reference for the monthly consumption of a building. Some energy providers have a more detailed record regarding the energy off-takes of their clients. In Luxembourg, the Administration des Bâtiments Publics (ABP), which owns the educational buildings under study, has an energy management system (EMS) that keeps records of the historical consumption of its buildings. The energy supplier delivers these on a 15-minute to hourly basis, allowing further analyses, such as evaluation of consumption patterns and general changes in energy performance. The information that is not available in the database, requires the analysis of energy bills or similar control done by the local staff.

In order to gain a deeper understanding of the electricity consumption patterns within a building, additional measurements are conducted using both fixed and mobile electricity meters, as presented in **Annex III**. The selection of an appropriate solution is determined according to the availability of equipment, monitoring strategies and, most importantly, access to electrical cabinets.

3.3.4. Building physics

Evaluating building physics is essential when assessing the energy performance of a building because it addresses the fundamental interactions between materials, environmental conditions, and the building envelope. This includes the study of thermal dynamics, moisture transfer, and airflow, which are critical for understanding heat loss, insulation efficiency, and indoor environmental quality. A comprehensive understanding of building physics allows for more accurate energy modelling, and the identification of energy savings measures, leading to reduced energy consumption and improved sustainability outcomes.

The thermal transmittance of a determined building component can be obtained either by using the thermal conductivity of the different elements composing a specific structure or by using a non-destructive method called the heat flow meter. The theoretical method and the heat flow meter test are described in detail in **Annex IV**.

Building thermography is a non-destructive measurement technique, that uses a thermal camera to verify the temperature distribution of a surface regarding its infrared radiation emission. Its working principle is presented in **Annex V**. The analysis of the temperature distribution is used to detect thermal bridges and air leakages which lead to transmission and ventilation losses.

Finally, the air change rate of a building, which is the number of times that the complete volume of air in a building is replaced per hour, can be quantified through the utilisation of various methodologies. In this analysis, the blower-door test and the CO_2 concentration decay method, presented in **Annex VI**, are employed to evaluate the airtightness of the building.

3.3.5. Comfort parameters

The comfort assessment includes the analysis of the radiant temperature, air temperature, relative humidity, CO_2 concentration, illuminance, air velocity, metabolic activity, clothing insulation and perceived comfort. The comfort parameters are monitored using different devices, as detailed in **Annex VII**.

Information about the clothing levels of the building users, used to assess thermal insulation, as well as their perceived comfort, referring to how occupants experience the indoor environment, is gathered through user questionnaires. These surveys ask participants to evaluate their comfort across multiple parameters, as detailed in **Annex VIII**.

3.4. Data analysis

This chapter outlines the approaches adopted to validate and prepare the collected data for subsequent analysis. The data are processed to obtain meaningful information related to energy- and carbon-saving opportunities and to evaluate their effectiveness.

Table 3.5: Types of data analysis

Type of data collection	Description	Details	Building
Energy data treatment (**Step 2**)	Validation of energy consumption data	Section 3.4.1	Buildings A, B, C and D
	Specific heat and electricity consumption	Section 3.4.1	Buildings A, B, C and D
	Energy consumption normalisation	Section 3.4.1	Buildings A, B, C and D
Electricity consumption analysis (**Step 2**)	Electricity consumption patterns	Section 3.4.2	Buildings A, B, C and D
	Baseload consumption	Section 3.4.2	Buildings A, B, C and D
	Consumption distribution	Section 3.4.2	Buildings A, B, C and D
Thermal consumption analysis (**Step 2**)	Thermal model	Section 3.4.3	Building B

The methodology applied for this analysis is summarised in **Table 3.5**, which also indicates which buildings from the case study were assessed using each specific procedure.

3.4.1. Energy data treatment

Before employing the collected energy data, cleaning, processing, and preparing is necessary to ensure representativity, and to allow further comparison. In this session, the methods to validate and prepare the information for further analysis is presented.

Validation of energy consumption data

The available database combined with local control provides an important amount of data regarding the energy consumption, allowing several analyses to assess the energy consumption within the buildings and their behaviour over the years. However, before application in technical analysis, the obtained data must be evaluated and prepared, as further described:

- Identification: Especially when it comes to older buildings sometimes the systems and their connections are not well registered and identified. Therefore, it is important to verify physically the central meter.
- Connections: The connection plans provide information regarding the energy distribution within the building, allowing the correlation with technical installations and reference areas. However, this is normally not the case in older systems, with outdated plans. This information is verified with local staff and further measurements.
- Data: The data is evaluated to ensure it reflects reality.
  - Unit: The unit of the data set must be identified and converted to a reference unit, in this case [kWh].
  - Missing data: blank periods in the dataset can appear due to communication issues. These need to be identified and verified to ensure that they do not influence the overview.
  - Behaviour: Historical data is compared over periods with similar activities to validate the behaviour of consumption. Important variations indicate the need for verification. In this step, the adoption of new systems or changes in operational settings are identified.
  - Renewables: The integration of renewable must be considered, to ensure that real consumption is evaluated. The use of renewables has a positive impact on reducing carbon emissions, which can be potentialized when aligned with an optimised operation. This is reached by monitoring the real consumption, independently of what is coming from the grid and what is supplied by the power plant. Otherwise, the use of renewables directly on-site can mask a low operational performance, giving the false impression that the building is consuming less energy than it actually does. Therefore, in this stage of the analysis, only the real consumption is considered.

Specific heat and electricity consumption

To assess the energy performance of the buildings, the specific energy consumption must be calculated as defined by Delmonte et al. (2025) [105]. This involves dividing the total thermal energy consumption by the total heated gross floor area, while the total electricity consumption is divided by the reference gross floor area, as outlined in **3.3.2 Building characteristics and techniques**.

According to the Luxembourgish energy efficiency regulation [74], the energy reference area of a building is defined as the conditioned portion of the net surface within the building envelope, which typically represents between 80% and 85% of the gross floor area. However, since some of the benchmarks used in this study, such as those in **Table 2.2** and **Table 2.3,** are based on gross floor area, the analyses in this work follow the same approach. To ensure clarity, the reference areas used for the educational buildings are always clearly specified.

Energy consumption normalisation

Energy consumption normalisation is used to neutralise the impact of meteorological conditions and allow performance comparison. This approach can be applied when comparing data from buildings situated in different climate regions, but also to compare yearly performances from the same building.

The historical data on thermal consumption is significantly influenced by meteorological conditions prevailing over the analysed years, internal and solar gains, thermal inertia, or domestic hot water supplies, among others. In order to reduce the influence of the weather conditions and the temperature difference between in and outside from the energy performance analysis, a widely used compensation approach to normalise the energy consumption with regard to heating degree days [79], is adopted as presented in **Equation 3.1**.

The Heating Degree Days (HDD) of a certain period, typically year, are calculated considering the difference between the internal and the external temperatures, reflecting the need for heating at that time. In Luxembourg, HDD values are provided by the Service de Contrôle et de Réception du Bâtiment (SCRB) [106]. The calculation assumes an average daily temperature of 15°C, which represents the threshold for heating. When the outdoor temperature falls below this value, heating is considered necessary to maintain the desired indoor temperature of 20°C.

Equation 3.1: Normalised thermal energy consumption using Heating Degree Days (HDD)

$$E_{norm} = E_{year} \times \frac{HDD_m}{HDD_{year}} \quad (3.1)$$

where:

E_{norm}	normalised annual thermal energy consumption of the building for average climate conditions [kWh]
E_{year}	measured thermal final energy consumption of a specific year [kWh]
HDD_m	mean Heating Degree Days for a long period of time in this region [Kd]
HDD_{year}	Heating Degree Days of the analysed year [Kd]

The average (HDD_m) corresponds to the mean of the annual HDD values (HDD_{year}) from 2017 until 2024. Whereas the annual HDD values for each year are obtained directly from the database and shown in

Table 3.6.

Equation 3.2: Mean heating degree days

$$HDD_m = \frac{\sum_{i=1}^{n} HDD_{years_n}}{n} \quad (3.2)$$

where:

HDD_m	mean Heating Degree Days for a long period of time in this region [Kd/a]
HDD_{year_n}	Heating Degree Days of each year in the historical period [Kd/a]
n	number of years in the historical period [-]

Table 3.6: Annual heating degree days data for Luxembourg from 2017 to 2024 [106][106]

Heating Degree Days (HDD)	2017	2018	2019	2020	2021	2022	2023	2024	Average
HDD_{year} [Kd/a]	3365	3126	3272	2968	3565	3056	3114	3301	3221
$\frac{HDD_m}{HDD_{year}}$	0.96	1.03	0.98	1.09	0.90	1.05	1.03	0.98	1.0
Number of heating days	256	225	254	231	261	207	204	206	231
Daily degree days [Kd/d]	13.1	13.9	12.9	12.8	13.7	14.8	15.3	16.0	13.9

The energy performances of the buildings are obtained by comparing the average annual specific consumption of electricity and thermal energy with local benchmarks. Energy consumption above national averages indicates that the building is consuming more than the average of similar structures, with similar activities, in the same meteorological context, indicating that there are opportunities to save energy.

3.4.2. Electricity consumption analysis

In the context of this study, the analysis of the electricity consumption comprises the evaluation of the consumption patterns, the analysis of baseload consumption during empty hours, and the consumption distribution according to the usage activities. These allow for the identification of consumption deviations and savings opportunities.

Electricity consumption patterns

The electricity consumption patterns are identified from the comparison between data from the same period. In this study, different approaches are adopted. The 15-minute consumption data is compared in a yearly basis. The analysis of historical data in a yearly basis allows to define consumption patterns regarding seasonal and occupancy influences. This analysis allows to identify peaks and baseloads, and to establish a typical profile, giving indications on consumption deviation, to be verified.

The variation in data granularity enables valuable assessments. Analysing the average consumption per hour for each day of the week reveals correlations with occupancy, while comparing different weeks throughout the year also highlights the further influence of the weather.

Another approach for identifying the energy consumption variation with regards to occupancy, is to establish a yearly heatmap, with hourly consumptions. The heatmap is a visual approach used to analyse energy consumption patterns by representing energy usage data in a colour-coded matrix. Colour intensity indicates the level of energy consumption, allowing patterns and trends to be easily identified. This method is particularly effective for detecting recurring usage trends, peak demand periods, and areas of consistently high or low consumption. This analysis provides valuable information to verify mismatch between demand and consumption.

This analysis supports better energy management strategies, informing decisions on behavioural changes, and scheduling adjustments to reduce overall energy demand in school buildings.

Baseload consumption

The baseload is the minimum constant power requirement of a building. It leads to an energy consumption which happens independently of user presence. In this study, the baseload consumption is determined through the analysis of a graphical technique called duration line method. It represents the distribution of the power requirements over a specific period, typically arranged in descending order. This curve reveals how frequently different power levels occur.

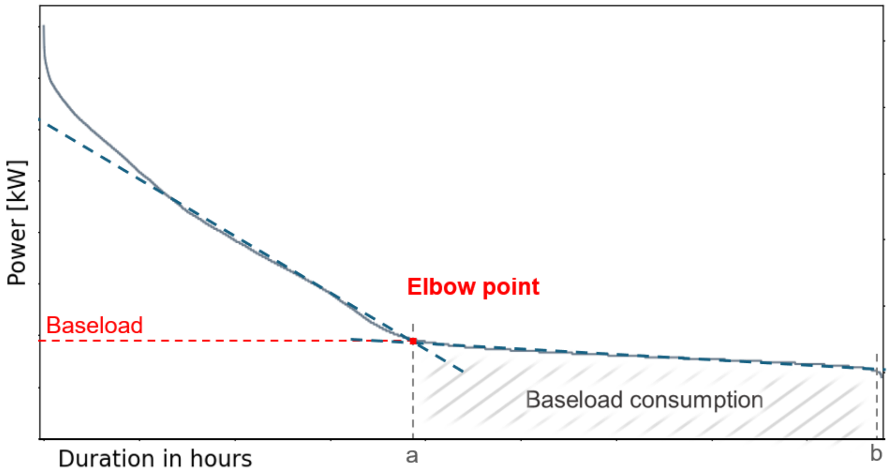


Figure 3.2: Representation of the elbow point, the baseload, and the baseload consumption

The baseload is determined by identifying the point on the curve where the rate of power variation shows a significant decrease, known as the knee or elbow point. The energy consumption corresponding to the baseload is derived from this power multiplied by the number of operating hours when it occurs, as shown in **Figure 3.2**.

Equation 3.3: Baseload consumption

$$E_{bl}(t) = \int_a^b P(t)\,dt \qquad (3.3)$$

where:

E_{bl}	baseload consumption [kWh/a]
t	period [h/a]
a	beginning of baseload occurrence [h]
b	end of baseload occurrence [h]
$P(t)$	power [kW]

This information is particularly useful for assessing energy efficiency and detecting potential energy-saving opportunities, as it highlights the portion of consumption that remains relatively unchanged regardless of external factors such as occupancy or operational schedules. This enables the implementation of strategic measures without compromising user comfort.

Consumption distribution

The analysis of energy distribution across different utilisation categories within educational facilities is essential for understanding consumption patterns and identifying opportunities for energy savings. Schools typically have a wide spectrum of energy demands, including heating, lighting, digital consumers, among other more specific activities. The process of categorising and visualising energy use according to each category, enables to identify the most energy intensive systems or activities.

Load profiling and sub-metering provide information concerning energy distribution across different spaces, such as classrooms, offices, kitchens, and sports facilities. Identifying baseload consumption (such as standby power for IT equipment or overnight heating) can help in targeting reductions through energy efficiency measures. Additionally, comparing energy use during occupied and unoccupied periods can highlight performance gaps and potential savings.

3.4.3. Thermal consumption analysis

The thermal consumption analysis consists of using the collected data to analyse the heat consumption distribution within the building. Considering the granularity of the collected data, and the challenges to isolate the consumption of parts of a building, in this analysis a thermal model is used. The thermal model is developed based on project information and local measurements, and it is validated by the overall measured consumption.

The thermal model is developed using the software LESOSAI which is mainly used for ecological and energy certification of buildings in several countries since the parameters change according to the chosen standard or label.

Among the available standards, LESOSAI proposes a stationary energy balance of the building, which provides a good approximation to identify the energy losses and evaluate the thermal energy performance of a building. The thermal balance is done following ISO 13790:2008 which gives calculation methods for the assessment of the annual energy use for space heating and cooling of a building. It provides an overview of the energy flows within the building, based on the calculation of heat transfer by transmission and ventilation, the contribution of internal and solar heat gains and the annual energy needs for heating and cooling, to maintain the specified required temperatures.

The thermal model provides a breakdown of heat losses across the various building components. It consolidates the information obtained during the measurement phase, and its accuracy depends on the quality of the input data. Once validated, the model serves as a tool to evaluate potential energy-saving measures.

In buildings, it is often difficult to isolate a single room when analysing thermal consumption. Therefore, validating the thermal model requires a careful comparison between its outputs, and the monitored, measured, and observed conditions in reality.

The analysis presented in this study are realised using the data collected following the methodologies presented in **3.3 Data collection**, in combination with literature values. The results are validated through the thorough comparison with the information obtained from monitored consumption.

3.5. Impact of energy- and carbon-saving interventions

The studied measures are presented in **6 Energy- and carbon-saving interventions**. The energetic impact of measure, as well as the impact in carbon emissions, and the economic aspect are realised based on the methodology presented below.

Table 3.7: Types of impact analysis of the intervention measures

Type of data collection	Description	Details	Building
Impact of energy- and carbon-saving interventions (**Step 3**)	Analysis of added embodied energy and operational savings of the intervention measures	Section 3.5.1	Buildings B, C and D
	Analysis of embodied carbon and operational savings of the intervention measures	Section 3.5.2	Buildings B, C and D
	Economic analysis of intervention measures considering the investments and differences in operational costs	Section 3.5.3	Buildings B, C and D

The methodology applied for this analysis is summarised in **Table 3.7**, which also indicates which buildings from the case study were assessed using each specific procedure.

3.5.1. Energetic impact of interventions

The energy assessment of intervention measures encompasses not only the reduction in operational energy consumption, but also the embodied energy associated with the production of new materials added during renovation, and with the production of renewable energy.

This analysis evaluates the effect of physical renovations and operational modifications on energy consumption and carbon emissions within existing educational facilities. Therefore, the embodied or grey energy analysis refers to the added energy of the interventions, to allow the comparison with the operational energy savings, and not a full analysis of the buildings.

The embodied energy of the materials used in intervention measures to reduce energy consumption is obtained from the environmental product declaration (EPD). Such declarations are emitted by manufacturers, and they are accredited by verifying bodies. In this analysis, the adopted references are publicly available in the Ökobaudat databas[107].

Each environmental product declaration indicates the non-renewable energy required in the production of the materials added to the buildings during interventions, known as total use of non-renewable primary energy resources (PENRT). This information is provided for a defined unit of the product. The identification of the total added primary embodied energy for the intervention measures is obtained by multiplying it by its total quantity. This analysis provides the added primary embodied energy of each intervention, to allow later comparison with the saved operational energy, and identify the final energetic impact of the proposed interventions.

The energy savings in the operational phase are obtained from the analysis of the changes in the operational settings, or from the reduction in heat losses related to the improvement of thermal resistances of building components.

The reduction in the final energy consumptions is converted to primary energy to allow comparison with the primary embodied energy obtained from the environmental product declaration. This is realised using the primary energy factors from the Luxemburgish directive concerning the energy efficiency of buildings, as presented in **Table 3.8** [74].

The primary energy factor for heat supplied by a district heating plant composed of multiple combined heat and power systems, where half of the heat is produced using natural gas and the other half using wood pellets is calculated following the weighted primary energy factor, presented in **Equation 3.4**, from the Luxemburgish energy efficiency of buildings directive [74].

Equation 3.4: Weighted primary factor [74]

$$e_p = n_{natural\ gas} \times e_{p\ natural\ gas} + n_{wood\ pellets} \times e_{p\ wood\ pellets} \tag{3.4}$$

where:

e_p	weighted primary energy factor
$n_{natural\ gas}$	part the heat produced from natural gas
$e_{p\ natural\ gas}$	primary energy factor for district heating with combined heat and power systems operating with natural gas
$n_{wood\ pellets}$	part the heat produced from wood pellets
$e_{p\ wood\ pellets}$	primary energy factor for district heating with combined heat and power systems operating with wood pellets

$n_{natural\ gas} + n_{wood\ pellets} = 1$

Table 3.8: Primary energy factors according to the final energy, production technology and fuel based on the Luxemburgish energy efficiency of buildings directive, before and after the latest revision in 2021 [74]

Final energy	Technology	Fuel	Primary energy factor before 2021 [kWh_p/kWh]	Primary energy factor 2021 [kWh_p/kWh]
Heat	Heating boiler	Heating oil	1.10	1.10
	District heating from combined heat and power systems	Natural gas	0.62	1.29
		Wood pellets	0.00	0.00
		Weighted (50% - 50%)	0.31	0.65
Electricity	Electricity mix		2.66	1.50

The primary energy consumption is calculated, as presented in **Equation 3.5**.

The division of the total primary embodied energy by the yearly primary energy saved from each intervention indicates the compensation time, which represents the number of years necessary to compensate the added grey energy, as presented in

Equation 3.6.

Equation 3.5: Primary energy per final energy type

$$E_{p_{saved_i}} = e_{p_i} \times E_{f_{saved_i}} \tag{3.5}$$

where:

$E_{p_{saved_i}}$	saved primary energy [kWh$_p$]
e_{p_i}	primary energy factor type i [kWh$_p$/kWh]
$E_{f_{saved_i}}$	saved final energy type i [kWh]

Equation 3.6: Energy compensation time

$$Energy\ compensation\ time = \frac{\mathrm{E}_{p_{\text{embodied energy}}}}{E_{p_{saved}}} \tag{3.6}$$

where:

$Energy\ compensation\ time$	time necessary for energy savings compensate the added embodied energy [years]
$\mathrm{E}_{p_{\text{embodied energy}}}$	primary embodied energy [kWh$_p$]
$E_{p_{saved}}$	yearly saved operational primary energy [kWh/a]

Operational energy savings beyond the compensation time leads to yearly carbon emission savings.

3.5.2. Impact of interventions on carbon emissions

The equivalent embodied carbon emissions associated with the intervention measures aimed at improving the energy performance of buildings are derived from the Environmental Product Declarations (EPDs) of the materials used, as provided by the Ökobaudat database [107]. The analysis accounts for the climate change factor, calculated for each product based on the equivalent embodied carbon emissions generated during the product stage, which includes raw material supply, transport, and manufacturing (A1-A3). Where applicable, the end-of-life stage, encompassing waste processing and disposal (C3–C4), is also considered, as illustrated in **Figure 2.1**.

The savings in carbon equivalent emissions from the interventions proposed in this study is realised considering the yearly reductions in carbon emissions after the compensation time, regarding eventual embodied energy additions. These yearly reductions are calculated based on the environmental factor defined in the Luxemburgish directive concerning the energy efficiency of buildings, concerning the type of saved final energy [74].

Table 3.9: Carbon emission factors according to the final energy, production technology and fuel based on the Luxemburgish energy efficiency of buildings directive (2021) and the Base Carbone of ADEME (2020) [74][108]

Final energy	**Technology**	**Fuel**	**Environmental factor [kgCO2/kWh]** [74]	**ADEME [kgCO2/kWh]** [108]
Heat	Heating boiler	Heating oil	0.300	0.324
	District heating from combined heat and power systems	Natural gas	0.258	0.205
		Wood pellets	0.000	0.014
		Weighted (50% - 50%)	0.129	-
Electricity	Electricity mix		0.367	0.410

The emission factor for heat supplied by a district heating plant composed of multiple combined heat and power systems, where half of the heat is produced using natural gas and the other half using wood pellets is calculated following the weighted environmental factor, presented in **Equation 3.7**, from the Luxemburgish energy efficiency of buildings directive [74].

Equation 3.7: Weighted environmental factor [74]

$$e_{CO_2 w} = n_{natural\ gas} \times e_{CO_2\ natural\ gas} + n_{wood\ pellets} \times e_{CO_2\ wood\ pellets} \tag{3.7}$$

where:

$e_{CO_2 w}$	weighted environmental factor
$n_{natural\ gas}$	part of the heat produced from natural gas
$e_{CO_2\ natural\ gas}$	environmental factor for district heating with combined heat and power systems operating with natural gas
$n_{wood\ pellets}$	part of the heat produced from wood pellets
$e_{CO_2\ wood\ pellets}$	environmental factor for district heating with combined heat and power systems operating with wood pellets

$n_{natural\ gas} + n_{wood\ pellets} = 1$

The reductions in the yearly carbon emissions obtained from the product of the environmental factors by the corresponding yearly saved energy, as presented in **Equation 3.8**.

Equation 3.8: Yearly carbon savings per final energy type

$$Yearly\ carbon\ savings_i = e_{CO_{2i}} \times Yearly\ energy\ savings_i \qquad (3.8)$$

where:

$Yearly\ carbon\ savings_i$	yearly carbon savings for final energy type i [kgCO_2]
$e_{CO_{2i}}$	environmental factor for final energy type i [kgCO_2/kWh]
$Yearly\ energy\ savings_i$	yearly energy savings for final energy type i [kWh]

Dividing the total embodied carbon equivalent emissions by the annual carbon savings achieved through each intervention yields the carbon compensation time, representing the number of years required to offset the additional embodied carbon introduced by the measure, as presented in **Equation 3.9**.

Once the carbon compensation time is reached, the intervention begins to generate benefits. From that point onwards, the reduction in operational energy demand translates into recurring annual carbon savings. These savings accumulate over the remaining lifespan of the building component or system, reinforcing the long-term value of the intervention measure. In this way, the initial embodied carbon associated with the intervention is compensated, and the measure contributes positively to the overall carbon balance of the building.

Equation 3.9: Carbon compensation time

$$Carbon\ compensation\ time = \frac{Embodied\ carbon\ emissions}{Operational\ carbon\ savings} \qquad (3.9)$$

where:

$Carbon\ compensation\ time$	time necessary for operational carbon savings compensate the added embodied carbon [years]
$Embodied\ carbon\ emissions$	embodied carbon equivalent emissions [kgCO_2]
$Operational\ carbon\ savings$	yearly saved operational carbon emissions [kgCO_2/a]

The methodology developed in this chapter applies this principle systematically to each of the analysed carbon-saving interventions. This enables a transparent comparison between interventions, supports the identification of the most effective strategies.

3.5.3. Economic impact of interventions

The economic impact of energy- and carbon-savings interventions in this study is based on the calculation of payback time, which provides a straightforward measure of the period required to recover the initial investment through energy cost savings. This approach was chosen to minimise uncertainties associated with more complex economic indicators, such as net present value or internal rate of return, which depend on assumptions about discount rates, inflation, and future energy prices.

The payback time, referring to the time taken to recover the initial investment costs, is calculated considering the **Equation 3.10**. It is used to calculate the investment return.

Equation 3.10: Payback time

$$Payback\ Time = \frac{Investment}{Annual\ Cash\ Flow} \tag{3.10}$$

The investments of the interventions related to renovations are obtained from commercial quotations validated by database references. The quotes are obtained from companies working in Luxembourg, while the database adopted in this analysis refers to the German database called SIRADOS. SIRADOS stands for Standardised Information for Rationalization, Tendering, Data Organization, and Standardisation, and it provides standardised, up-to-date data on construction costs, unit prices, and service descriptions for planning, tendering, and cost control in building projects. It serves as a reference to describe services, quantify activities, and evaluate commercial quotes [109].

Table 3.10: Reference operational energy costs defined based on energy bills (2022)

Final energy	Technology	Energy cost [€/kWh]
Heat	Heating boiler	0.08
	District heating from combined heat and power systems	0.10
Electricity	Electricity mix	0.35

The analysis uses reference operational unit costs for electricity and heat specific to the studied buildings. These values, expressed in €/kWh, represent the baseline against which potential savings are evaluated. The reference costs are obtained from energy bills from 2022 and are presented in **Table 3.10**, providing a transparent basis for the calculation of the payback times.

The operational energy savings for each intervention are calculated in **6 Energy- and carbon-saving interventions**, based on the specific measures applied to the analysed buildings, and is calculated based on **Equation 3.11**.

Equation 3.11: Yearly operational savings

$$Annual\ Cash\ Flow = E_{f_{saved_i}} \times Energy\ cost \tag{3.11}$$

where:

$Annual\ Cash\ Flow$	annual cash flow generated by the energy savings
$E_{f_{saved_i}}$	saved final energy type i [kWh]
$Energy\ cost$	specific energy cost [€/kWh]

The outlined approach is applied to all the studied carbon-saving interventions, thus enabling the analysis of the payback time of the different measures.

3.6. Performance assessment of interventions

The energy- and carbon-saving interventions applied to the studied educational buildings are energetically and economically assessed. The reduction in carbon emissions is analysed based on the added embodied energy and the savings in operational energy. The methodology for such analysis is presented in the following subchapters.

Table 3.11: Types of performance assessment

Type of data collection	Description	Details	Building
Performance assessment of interventions (**Step 4**)	Comparison of intervention measures in terms of energy	Section 3.6.1	Buildings B and C
	Comparison of intervention measures in terms of carbon emissions	Section 3.6.2	Buildings B and C
	Economic comparison of intervention measures in terms	Section 3.6.3	Buildings B and C
	Physical and perceived comfort analysis before and after interventions measures	Section 3.6.3	Building B
	Integrated performance indicator to support stakeholders in decision-making	Section 3.6.5	Building B

Table 3.11 outlines the methodology used for the performance assessment and specifies the procedures applied to each building in the case study.

3.6.1. Energetic assessment

The various intervention measures are compared in terms of energy-related investments, including embodied energy, as well as the resulting operational energy savings achieved through improved system performance and enhanced thermal behaviour of the building components.

This evaluation process enables the selection of interventions that are more effective and efficient in achieving significant energy savings. Moreover, it facilitates a comparative analysis of the performance of the remaining measures and the identification of opportunities for further improvement.

3.6.2. Carbon emissions assessment

The intervention strategies are also assessed with respect to their carbon impact, taking into account both embodied carbon equivalent emissions associated with materials and construction processes, and the reduction in operational carbon emissions resulting not only from decreased energy consumption but also from the adoption of renewable energy sources.

This assessment supports the identification of measures that contribute most effectively to carbon mitigation, while also allowing for the elimination of less impactful options. It further enables a comparative review of the strategies retained and highlights areas where additional reductions in emissions may be achieved.

3.6.3. Economic assessment

The intervention strategies are also evaluated from an economic perspective, primarily through the consideration of yearly savings and payback time. This metric provides a straightforward way to compare the economic feasibility of different measures. However, it is not equally applicable to all types of interventions.

Operational measures, for instance, generally require no upfront investment. As such, their evaluation cannot rely on payback time but instead only in the yearly savings, from the reduction in energy consumption. Renovation measures present another layer of complexity. In existing buildings, part of the costs is related to routine maintenance, which must be carried out regardless of energy efficiency objectives. While these interventions can lead to energetic and financial savings, decisions should not be based on payback time, but on the functionality of the building. Moreover, in Luxembourg, where energy prices are relatively low, investments in improving thermal resistance often result in particularly long payback periods.

The situation is even more complex when considering renewable energy integration. Depending on the solution, feasibility depend on the presence of supportive national frameworks, making it difficult to establish a reliable payback estimate. For this reason, and given the central role that budget and economic indicators play in decision-making, an integrated indicator is needed, to enable meaningful comparison between measures while capturing both economic and environmental dimensions.

3.6.4. Comfort assessment

Comfort is a subjective concept that is not only related to physical conditions, and can be influenced by the environment and the state of mind. However, these conditions can be measured and assessed using different tools [110]. This study monitors comfort parameters to guarantee that the energy-saving measures do not lead to negative impacts on how users feel inside the buildings, and to enhance engagement and acceptability in the process. It proposes the assessment of physical and perceived comfort in accordance with the ISO 7730 standard, by installing comfort sensors and distributing the perceived comfort questionnaires, presented in **Annex VIII - Perceived comfort questionnaires**.

Predicted mean vote and predicted percentage of dissatisfied

The evaluation of the perceived comfort is done using the predicted mean vote scale, a thermal comfort index that quantifies the average thermal sensation of occupants on a scale from -3 (cold) to +3 (hot). In the context of this study, the predicted mean vote is used to correlate measured physical values with perceived comfort.

Once the predicted mean vote is calculated, the predicted percentage of dissatisfied (PPD) can be determined. PPD is a quantitative measure that predicts the proportion of occupants likely to feel thermally uncomfortable in a given environment. It provides insight into overall thermal dissatisfaction by estimating the percentage of people experiencing discomfort, even under seemingly optimal conditions. Since thermal perception varies among individuals, this parameter helps assess local discomfort and refine indoor climate control strategies to enhance occupant comfort.

Equation 3.12: Predicted mean vote

$$PMV = [0{,}303 \cdot e^{-0{,}036Met} + 0{,}028]\{(Met - W) - 3{,}05 \times 10^{-3}[5733 - 6{,}99(Met - W) - p_a] - 0{,}42[(Met - W) - 58{,}15] - 1{,}7 \times 10^{-5} Met(5867 - p_a) - 0{,}0014Met(34 - t_a) - 3{,}96 \times 10^{-8} f_{cl}[(t_{cl} + 273)^4 - (\bar{t_r} + 273)^4] - f_{cl} h_c (t_{cl} - t_a)\}$$

$$t_{cl} = 35{,}7 - 0{,}028(Met - W) - I_{cl}\left\{3{,}96 \times 10^{-8} f_{cl}\left[(t_{cl} + 273)^4 - (\bar{t_r} + 273)^4\right] - f_{cl} h_c (t_{cl} - t_a)\right\} \quad (3.12)$$

$$h_c = \begin{cases} 2{,}38|t_{cl} - t_a|^{0{,}25} & for\ 2{,}38|t_{cl} - t_a|^{0{,}25} > 12{,}1\sqrt{v_{ar}} \\ 12{,}1\sqrt{v_{ar}} & for\ 2{,}38|t_{cl} - t_a|^{0{,}25} < 12{,}1\sqrt{v_{ar}} \end{cases}$$

$$f_{cl} = \begin{cases} 1{,}00 + 1{,}290 I_{cl}\ for\ I_{cl} \leq 0{,}078\ [\,m^2K/W] \\ 1{,}05 + 0{,}645 I_{cl}\ for\ I_{cl} > 0{,}078\ [\,m^2K/W] \end{cases}$$

where:

PMV	predicted mean vote [-]
Met	metabolic rate [W/m^2]
W	effective mechanical power [W/m^2]
I_{cl}	clothing insulation [m^{2}K/W]
f_{cl}	clothing surface area factor
t_a	air temperature [°C]
$\bar{t_r}$	mean radiant temperature [°C]
v_{ar}	relative air velocity [m/s]
p_a	water vapour partial pressure [Pa]
h_c	convective heat transfer coefficient [W/m^{2}K]
t_{cl}	clothing surface temperature [°C]

Note: 1 metabolic unit = 1 met = 58,2 W/m^2 / 1 clothing unit = 1 clo = 0,155 m^2 °C/W

The PPD is a key metric in thermal comfort analysis, indicating the proportion of individuals likely to feel uncomfortable in a given indoor environment. It is derived from the predicted mean vote (PMV). The relationship between PMV and PPD, determined by the Fanger equation, is nonlinear, meaning that even in optimal conditions (PMV = 0), at least 5% of occupants may still feel too warm or too cold.

The PMV and the PPD are calculated from the information regarding the physical comfort parameters, and subjects level of clothing insulation and metabolic activity. The results are obtained by using the Python package for thermal comfort [111].

Equation 3.13: Predicted percentage of dissatisfied

$$PPD = 100 - 95 \cdot e^{-(0{,}03353PMV^4 + 0{,}2179PMV^2)} \tag{3.13}$$

where:

PPD	predicted percentage of dissatisfied [%]
PMV	predicted mean vote [-]

The physical measurements are taken during a lecture and show the evolution of the comfort parameters while the students answer the comfort questionnaire. The students are in sitting position, and their metabolic activity is considered as 1 met, which corresponds to 58 W/m^2 of body surface. The information concerning the clothing is obtained through the questionnaires, and the PMV and PPD are calculated based on the median values in clo. The median value is adopted as reference for further analysis considering that it represents the required clothing for the climate conditions during the data collection.

Surveys are inherently subjective, allowing for personal interpretation, and consequently resulting in significant variations in specific answers. Furthermore, during the course of the surveys it was observed that some participants would provide information regarding their clothing for outside activities, rather than the actual clothing they were wearing in the classroom, which significantly changes during the winter months. It has been observed that a common issue is the omission of all closing pieces, resulting in lower insulation values. **Figure 3.3** shows the PMV and PPD relation for the physical measurements taken during the survey on 11/03/2025 at the classroom called Reference Room, for the extreme (min and max), the median and the average clothing levels. It is observed that PMV can vary considerably according to the clothing level, from -1.9 to 0.1, which represents 33% of the full range (-3 to 3), for the same physical conditions. Therefore, for further analysis, the median value of clothing obtained from the questionnaires is used in the **Equation 3.12**.

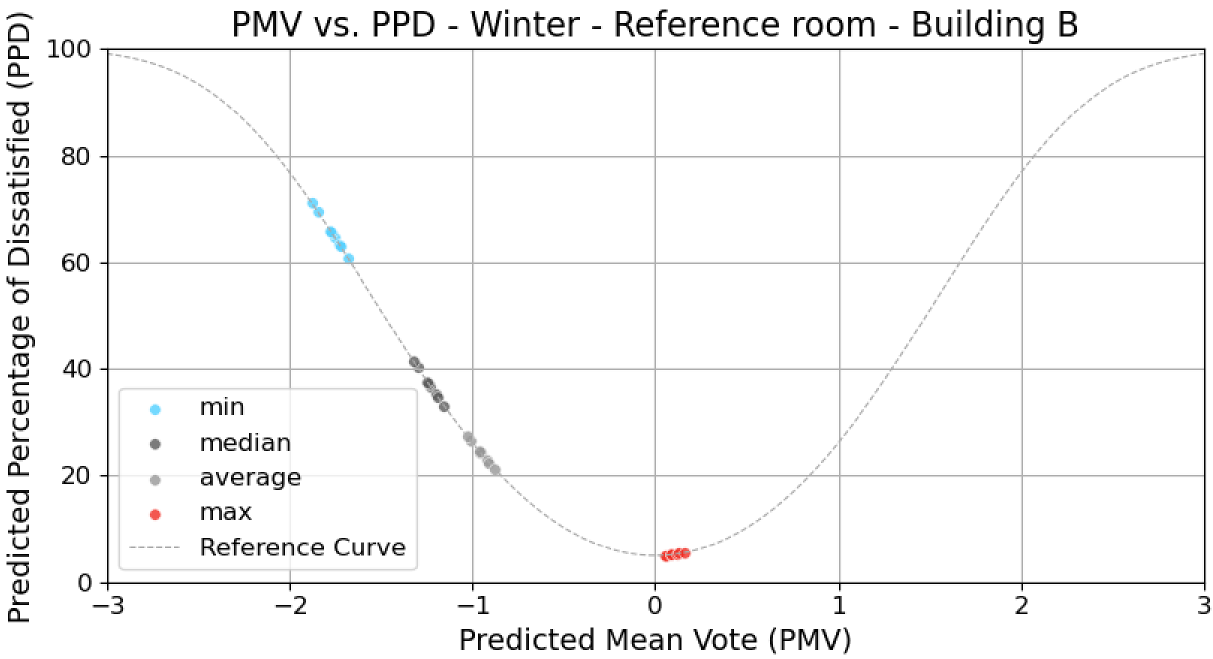


Figure 3.3: PMV and PPD results calculated from the physical measured points for the min, max, median and average clothing levels

The PMV and PPD are initially calculated for each data collection, allowing to identify patterns for each room, and the comparison of performances.

Perceived comfort analysis

The perceived comfort analysis is realised based on the results of the comfort questionnaires defined in **Annex VIII - Perceived comfort questionnaires**. The questions rating is divided in two types, one with answers ranging from 1 to 7, where 1 is negative and 7 is positive, and the second with answers ranging from -3 to 3, where the optimal condition is at 0. The second type aligns with the PMV ranges, allowing comparison.

The 18 questions related to perceived comfort are grouped according to their rating range, and the topics they assess. Group 1 focuses on general impressions and overall satisfaction, including items of indoor climate rating, satisfaction, and personal importance of this factor. The aspect of the overall feeling is also included in this group, to evaluate the impact of personal state of mind on perceived comfort. Group 2 addresses specific thermal comfort variables, such as temperature, humidity, and draft, which are the same physical measurements used in the PMV calculation. Group 3 refers to the personal rate of a longer scope of sensory factors, covering fresh air, temperature, light, air quality, acoustics, and smell. Lastly, Group 4 relates to options to control parameters of temperature, draft, windows, air quality, and light.

Table 3.12: Group of perceived comfort questions

Group	Description	Rate	Question number
Group 1	General impressions and overall satisfaction regarding the indoor climate	1 to 7 Where: 1 – bad 7 – good	Overall feeling, 6, 12 and 13
Group 2	Thermal comfort variables, related to PMV	-3 to 3 Where: 0 – optimal	1, 2 and 9
Group 3	Rating of parameters related to indoor climate	1 to 7 Where: 1 – bad 7 – good	3, 4, 5, 7, 8 and 10
Group 4	Desire to control comfort parameters	-3 to 3 Where: 0 – optimal	11, 14, 15, 16 and 17

The correlation between parameters is taken into account in the analysis, both to validate the results, particularly when strong correlations are expected, and to identify and establish new relationships between parameters.

Correlation between physical measurements and perceived comfort

This section examines the relationship between objective physical measurements and subjective perceptions of comfort. By comparing the calculated values of the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) with the responses from the comfort surveys, it is possible to assess the degree of correlation between the measured environmental parameters and perceived thermal comfort.

3.6.5. Integrated performance indicator

The integrated performance indicator assessment has been developed as a tool to assist stakeholders in overcoming the decision-making barriers that are in place. The study introduces a metric for the evaluation of the economic performance of different intervention measures, enabling a comparison of these measures while accounting for their potential for carbon emission reduction. This combined assessment is essential, as interventions can vary significantly in terms of investment requirements and their impact on operational costs, making direct comparisons otherwise challenging.

The avoided carbon cost (ACC) is a performance indicator that expresses the cost-effectiveness of an intervention in terms of euros spent per kilogram of CO_2 avoided. It combines financial and environmental perspectives by linking investment and savings with the associated carbon reductions. Mathematically, through **Equation 3.14**, the ACC is calculated by subtracting initial investment from the cumulative operational savings over analysed period, and dividing this balance by the net carbon savings achieved during the same period. Net carbon savings are determined by the yearly carbon reductions, adjusted to account for the time required to compensate for the embodied emissions of the intervention. This formulation ensures that both the financial payback and the carbon compensation time are consistently integrated, enabling direct comparison of different measures on a common basis.

Equation 3.14: Avoided carbon cost of intervention measures

$$ACC = \frac{(Yearly\ savings\ \times Op\ years\ ) - Investment}{(Op\ years - \ Carbon\ compensation\ time) \times Yearly\ carbon\ savings_i} \qquad (3.14)$$

where:

ACC	avoided carbon cost [€/kgCO$_2$]
$Yearly\ savings$	yearly reduction in energy bills [€/year]
$Op\ years$	number of operational years considered for the building in the analysis [years]
$Investment$	investment [€]
$Carbon\ compensation\ time$	time necessary for carbon savings compensate the added embodied carbon [years]
$Yearly\ carbon\ savings_i$	yearly carbon savings for final energy type i [kgCO$_2$/year]

It is important to note that **Equation 3.14** is only applicable to scenarios in which the analysed operational period years exceeds its carbon compensation time ($Op\ years$ *[years]*$>$ $Carbon\ compensation\ time$ *[years]*). In cases where the carbon compensation time is longer than the expected years of operation, no net carbon emissions are effectively avoided, and therefore the avoided cost of carbon cannot be calculated. Under such conditions, the metric becomes inapplicable, as the intervention fails to deliver measurable carbon savings within its operational lifetime.

Negative values indicate the net result from the investment, after subtracting operational savings from billing, expressed per kilogram of CO_2 saved during the analysed operational years, once the embodied emissions have been compensated. This represents the investment allocated as the expense required for each unit of CO_2 reduced, thereby quantifying the price of emission reduction. Conversely, positive values occur in cases where no upfront investment is required, or where the investment is fully compensated within the analysed operational period. In these situations, emission reductions are achieved in parallel with net economic savings, meaning the intervention not only offsets its initial costs within the defined timeframe but also delivers additional cost reductions per unit of CO_2 avoided. Therefore, the higher the ACC, the better the performance of the analysed intervention measure.

In the context of the relatively low energy prices in Luxembourg, investments aimed at reducing energy consumption are often not economically attractive. Nevertheless, such measures remain essential for meeting European carbon reduction targets and mitigating the impacts of climate change.

Consequently, rather than focusing solely on payback times, the integrated performance indicator prioritises the evaluation of the cost of avoided carbon emissions resulting from the implementation of each intervention, calculated using **Equation 3.14**.

The approach aims to enable a comparative analysis of the intervention strategies. In particular, the evaluation of the cost of avoided carbon emissions provides a valuable basis for selecting measures that, despite higher initial investment, deliver meaningful long-term environmental.

4. Behavioural approach

Educational buildings are concerned with a diverse group of stakeholders, each with distinct roles, responsibilities, and priorities. In Luxembourg, this complex ecosystem involves multiple actors: the building owner, who oversees infrastructure and manages service providers responsible for operations and maintenance; the Ministry of Education, which defines curricular guidelines; the school Director, who ensures the smooth daily operation of educational activities; the local staff, tasked with daily building upkeep; teachers, responsible for delivering lectures; students, focused on acquiring knowledge; and parents, invested in the well-being and development of their children. This diversity creates a complex web of interests and priorities, with significant variation in the degree of influence each group exerts over the operation of the building. These differing perspectives and responsibilities also shape how each stakeholder perceives their role in achieving energy savings, often resulting in varied levels of engagement and commitment to energy-efficient practices.

This chapter refer to the first step of the proposed four-step framework for reducing energy consumption and carbon emissions in post-primary educational buildings. It aims to identify stakeholders and engage them in process to improve effectiveness.

Two types of behavioural questionnaires were administered to building users and managers, as presented in **3.3.1. Behavioural survey**. The first aims to assess how users position themselves in relation to pro-environmental behaviours, while the second aims to understand the barriers faced by managers in implementing measures to reduce energy consumption and carbon emissions.

4.1. Pro-environmental behaviours among users

The pro-environmental behaviour to reduce energy consumption in educational buildings surveys realised in February and March 2025 at Building B shows that around 70% of the 92 participants consider engaging with it valuable and beneficial, as shown in **Figure 4.1** **Figure 4.2**, and **Figure 4.3**. Although less than 35% of people consider that they can control the measures to reduce energy consumption and 41% state that they do not have enough opportunities and resources, around 60% of them have the intention to engage, and already changes their lifestyle for a better environment. Regarding the influence of the opinion or the example of admired people, 45% of participants agreed, and between 45% and 50% did not have an opinion about it.

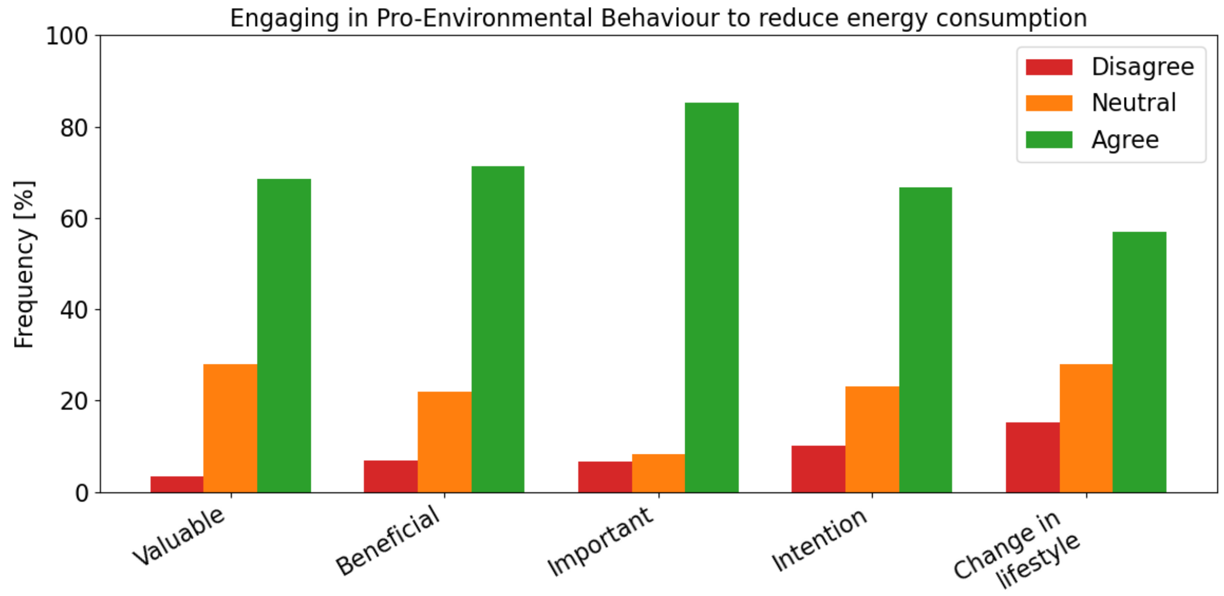


Figure 4.1: Results of the survey concerning engagement in Pro-Environmental Behaviour (Building B)

In terms of barriers to adhere to pro-environmental behaviours to reduce energy consumption in their educational building, 89% of the people agree that they know what to do, and 86% recognise it as important for them, **Figure 4.1**.

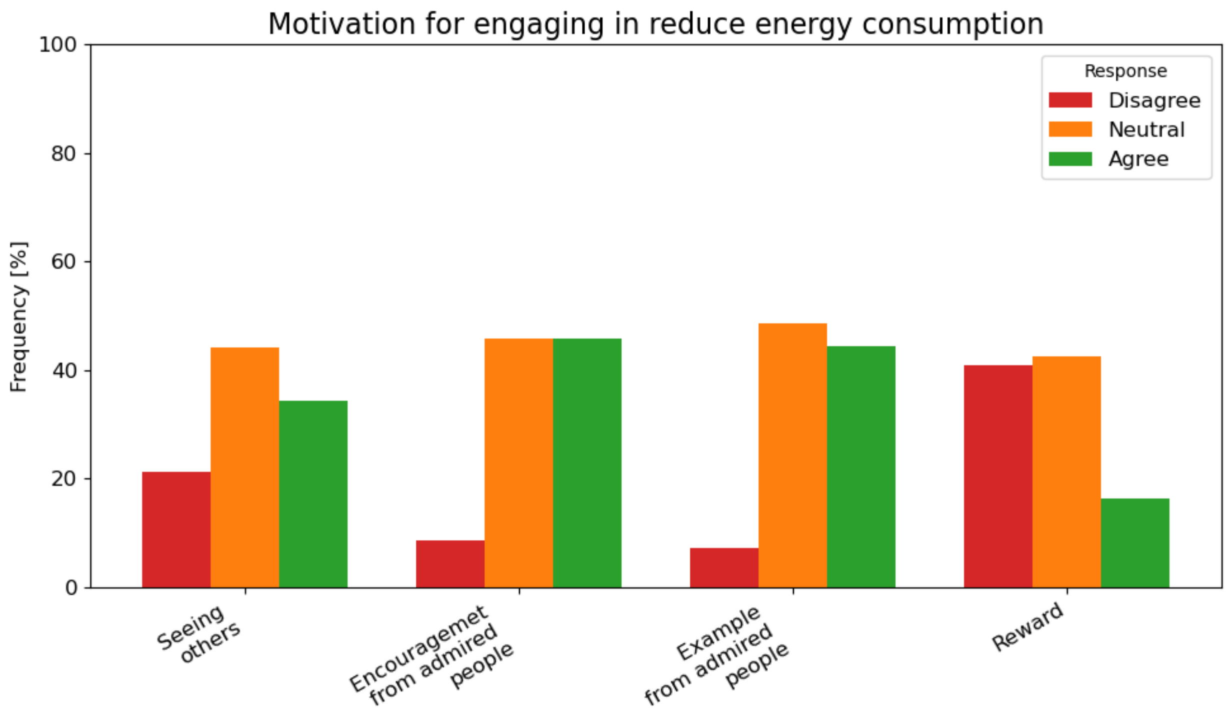


Figure 4.2: Results of the survey concerning the motivation to engage in Pro-Environmental Behaviour (Building B)

Regarding group effect, 45% of the participants do not have an opinion about the engagement of their colleagues. 40% of participants do not agree that engaging in such behaviours is inconvenient, following the positive approach observed before (**Figure 4.2**). Finally, only 16% of the people agree that they get rewarded for adopting pro-environmental behaviours to reduce energy consumption in their educational building (**Figure 4.3**).

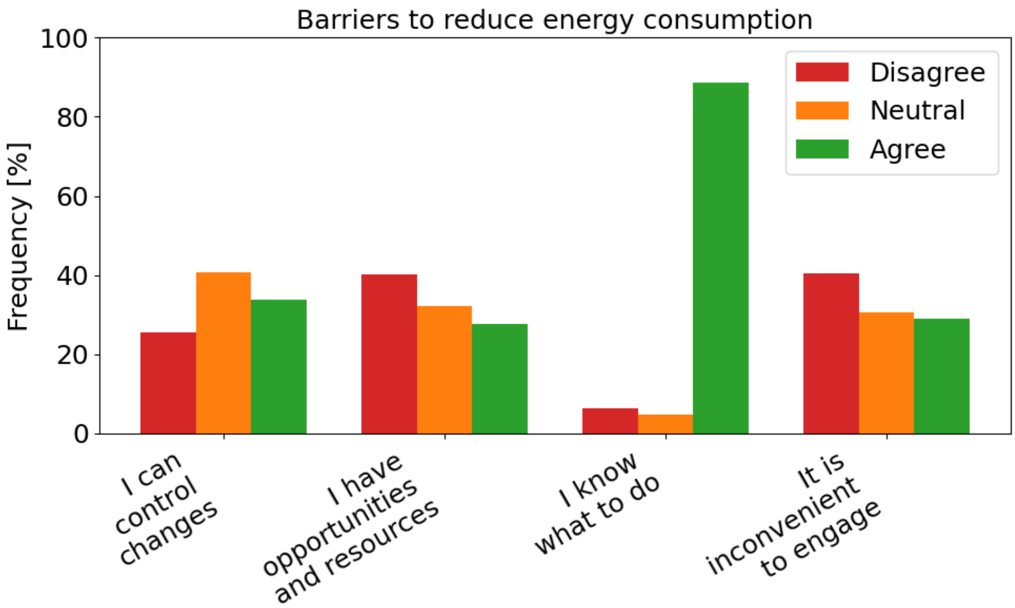


Figure 4.3: Results of the survey concerning the barriers to engage in Pro-Environmental Behaviour (Building B)

These results show an overall positive inclination towards engaging in pro-environmental behaviours to reduce energy consumption by the educational building users.

4.2. Energy and site managers

The questionnaire, which comprised four open-ended questions designed to identify the barriers encountered by energy and site managers when implementing interventions to reduce energy consumption in educational buildings (**3.3.1 Behavioural survey**), was integrated into an online questionnaire using SoSciSurvey. The questionnaire was disseminated to 13 energy managers and stakeholders, yielding a response rate of 54%.

The questions aimed to identify work responsibilities, the priority level of sustainability personally and for their institutions, the main barriers they face to implement intervention measures, and finally, if the company includes sustainable parameters as indicator.

Regardless of work responsibilities, all participants agreed that resource constraints are a key barrier to sustainability implementation. Participants in strategic roles mention budget while participants with multi-level engagement also focus on technical issues and practical application as well as lack of time and staff.

While most participants express a personal commitment, organizational implementation is often conditional on the budget. It is also observed that participants who felt aligned and empowered, report fewer barriers. Furthermore, two participants with matching personal and organisational values on sustainability, report unclear answers regarding the promotion of sustainability indicators.

Participants which rated sustainability with higher priority in their working places reported that sustainability is considered as a parameter for decision making. At the same time, low conditional integration of sustainability parameters seems to be related to more barriers being encountered. These results lead to the conclusion that barriers could be reduced, if companies established clear sustainability indicators.

These results underscore the importance of the first step in the proposed framework, which involves engaging stakeholders and understanding the specific challenges they face in implementing intervention measures. This early involvement enables more informed planning and decision-making, increasing the probability of achieving effective and sustainable outcomes.

4.3. Behavioural approach outcomes

The surveys conducted in early 2025 provide insights into both user perceptions and managerial perspectives on pro-environmental behaviours and energy-saving interventions in educational buildings.

From the perspective of building users (92 participants at Building B), the results indicate an overall positive inclination towards engaging in pro-environmental behaviours. Approximately two-thirds of participants recognise the value of such practices, intend to take part, or are willing to adapt their lifestyle to support environmental goals. However, more than one-third report limited control and insufficient opportunities or resources to reduce energy consumption effectively. The influence of admired people is not clear. Encouragingly, a majority feel knowledgeable about what to do and acknowledge the importance of these behaviours. These findings highlight a positive behavioural outlook but also reveal structural barriers that restrict effective participation.

The perspective of site managers further illustrates systemic challenges, beginning with the fact that only half of those invited chose to participate. Across roles, resource constraints, particularly regarding budget limitations, emerged as the dominant barrier to implementing sustainability interventions. Technical staff additionally cited practical and technical challenges, besides the lack of dedicated staff. Although most respondents expressed personal commitment to sustainability, organisational action was frequently conditional, shaped largely by financial resources and institutional priorities. Interestingly, participants whose personal values aligned closely with those of their organisation perceived fewer barriers. Notably, the results indicate the need for clear sustainability indicators at the organisational level, to facilitate smoother implementation and reduce obstacles.

Together, these perspectives emphasise both willingness and constraint. Building users and site managers alike demonstrate motivation to act, yet structural and resource-related barriers continue to hinder impact. The findings reinforce the importance of early stakeholder engagement, as proposed in the framework, ensuring that both user behaviour and managerial challenges are integrated into planning processes. Such an approach increases the likelihood of achieving effective, long-lasting energy reductions in educational buildings, as it enables the design of measures that address stakeholder challenges directly and provide targeted support to overcome barriers.

5. Energy audit of educational buildings in Luxembourg

An energy audit is a procedure designed to provide detailed information regarding the energy consumption profile of a specific activity, with the objective to identify and quantify potential energy savings and reduce related carbon emissions. Their implementation is defined through several norms and regulations, including the EN 16247-1. According to the European Directive 2023/1791, conducting an energy audit should be encouraged within public administrations [112]. In the context of this work, the energy audit—corresponding to Step 2 of the framework presented in **Figure 3.1**, is applied with a focus on educational buildings in Luxembourg. It provides a structured approach to systematically analyse energy consumption data and to identify high-impact, easy-to-implement savings opportunities in activities that show low performance when compared to established benchmarks.

The energy audit process, outlined in the flowchart presented in **Figure 5.1**, illustrates the methodological framework proposed in this study. This structure guides the analysis of the collected data to detect interventions that are relatively simple to implement, yet offer significant potential for reducing both energy consumption and associated carbon emissions.

The approach prioritises interventions that are both impactful and straightforward to apply, before progressing to more complex or less immediately beneficial measures. The focus lies in gaining a clear understanding of how, when, and where energy is consumed within the building, as well as identifying the specific equipment and systems involved, in order to assess performance and reveal opportunities for improvement.

As illustrated in **Figure 5.1**, the energy audit process is initiated with a data collection stage, which is structured in two distinct steps. The initial step focuses on assembling general background information required for a preliminary evaluation of the energy performance of the studied building. This includes collecting data on reference floor areas, electricity and heating consumption as described in **3.3.2 Building characteristics and techniques** and **3.3.3 Energy consumption**.

In order to meaningfully assess performance, it is crucial to identify relevant local benchmarks. This is commonly achieved by analysing historical consumption data from comparable buildings with similar operational characteristics, as discussed in **2.4.2 Benchmarks in educational buildings**.

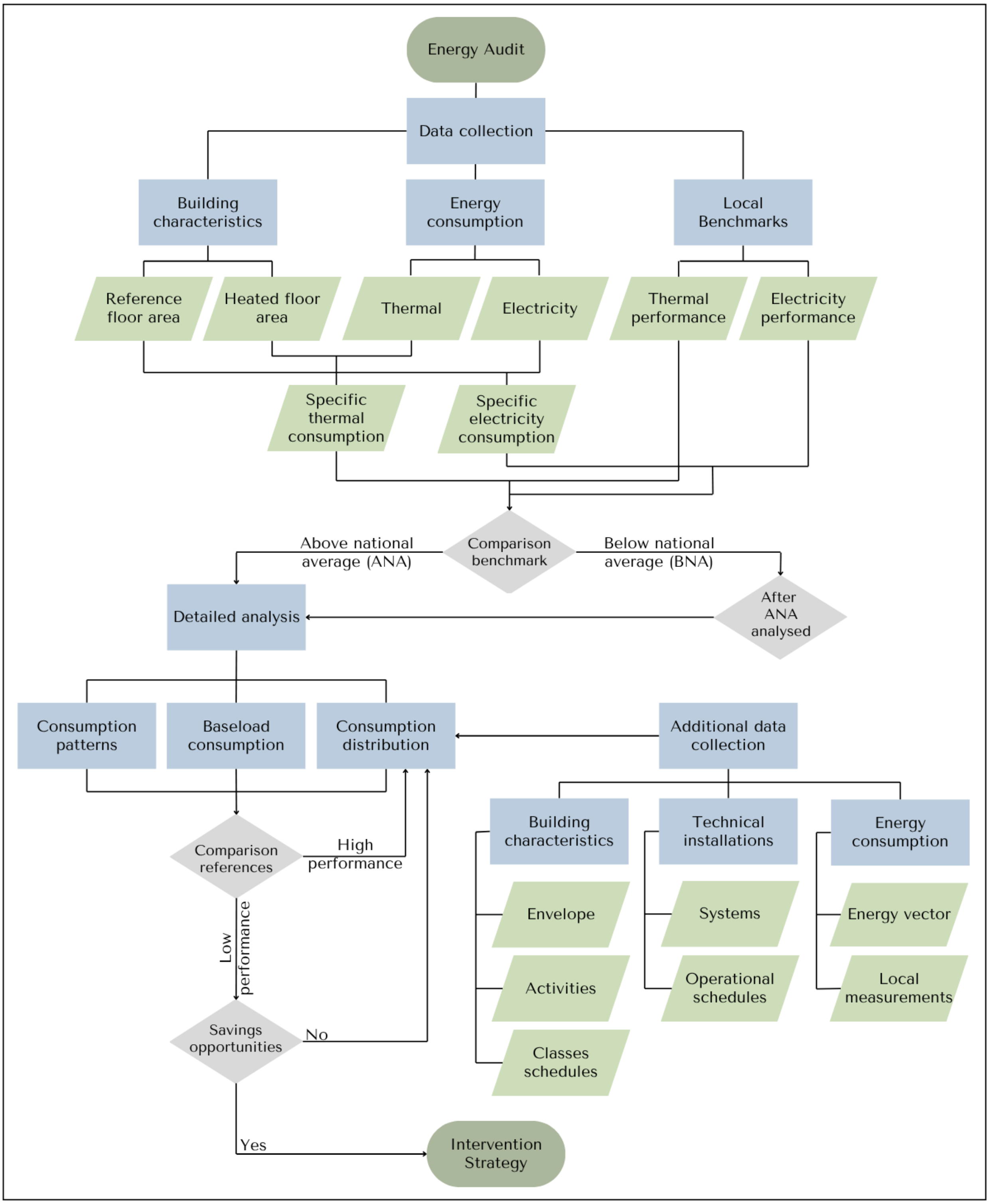


Figure 5.1: Energy audit process flowchart [105]

Comparing the overall energy consumption of the two buildings directly is not appropriate, as variations in their respective reference surface areas significantly may affect the total figures. To provide a more accurate assessment of energy performance, it is necessary to normalise the data by calculating the specific energy consumption, as described in **3.4.1 Energy data treatment**.

The evaluation of specific thermal and electricity consumption is conducted through comparison with local benchmarks. This initial comparison provides the necessary basis for determining where to focus the audit efforts. The strategy is built on identifying measures that have high impact yet do not require major investments or renovations, by targeting deviations in operational performance. Accordingly, further analysis focuses on areas with higher energy consumptions which are above reference values.

Specific consumption data that exceed benchmark values are prioritised for more detailed analysis. This includes a careful review of relevant information such as building characteristics, the envelope, occupancy profiles, space allocation, technical systems, operational schedules, energy vectors, and the distribution of energy use. These data are obtained through site inspections, analysis of architectural and technical documentation, and complementary on-site measurements, as outlined in Section **3.3 Data collection**.

With the additional information gathered, the consumption data are further examined to uncover patterns and trends, as presented in **3.4 Data analysis**. Yearly consumption is assessed to detect general tendencies, while its distribution over time helps to identify recurring patterns, baseload levels, and peak demand. These analyses allow for the detection of both operational inefficiencies and performance improvements, which often require further verification in relation to the technical systems and their control strategies. Seasonal variations are also considered to assess the influence of user behaviour and weather conditions.

Baseload consumption, understood as the energy use happening even when the building is unoccupied, represents a key area for savings. Optimising building operation during low-occupancy periods can yield substantial reductions in energy consumption without requiring significant investment or impacting user comfort. Since changes during these periods often go unnoticed by occupants, they offer a limited yet effective opportunity for optimisation. To determine the baseload, a combination of histogram analysis and duration line curves is used. While the histogram shows the distribution and frequency of consumption values, the duration curve provides a cumulative view, helping to identify the baseload threshold and interpret the data structure more effectively.

The audit also aims to determine how energy is distributed among systems and activities within the building. This is achieved by combining technical assessments with localised measurements, allowing the identification of high-consumption areas. A comprehensive understanding of energy demand across the building requires detailed monitoring and a thorough review of its functions and technical installations. Various use types are systematically categorised, and major consumers, typically equipment with high power demands or extended operating hours, are identified. Their consumption is then assessed through data collected from sub-metering, temporary instrumentation, or portable measurement tools, depending on accessibility and available resources. This combined approach provides a detailed understanding of energy flows throughout the building.

Identifying the highest energy flows helps determine which areas require more focused investigation. The same method is applied when comparing specific activities against relevant benchmarks. In general, systems or appliances with already high performance offer limited additional savings potential. In contrast, those operating below expected performance levels may offer meaningful opportunities for optimisation, which should be thoroughly assessed.

Once such opportunities are identified, the next step involves defining an intervention strategy. The proposed approach gives priority to the most accessible and impactful measures, addressing these first before undertaking a full assessment of the building. This does not exclude the identification of further opportunities in other systems. When additional audit resources are available, energy savings may also be achieved in areas already operating relatively efficiently.

After lower-performing systems are addressed, it may be beneficial to assess whether high-efficiency systems also present room for improvement. This is conducted through the same detailed analysis of building features, technical systems, and consumption distribution. The findings should be integrated into a broader intervention strategy to maximise overall energy and carbon savings.

5.1. Information collection

The energy audit involves several analyses of the building, requiring a clear understanding of its physical characteristics as well as its use distribution. For this purpose, technical visits are necessary to complement the information from the plans, especially for older buildings, where such documents are sometimes not very accurate.

5.1.1. Characteristics of the buildings

The four analysed educational buildings are located in Luxembourg, and information regarding the year of construction, as presented in **Table 3.1**, provides references for typical construction materials, and indications of their technical specifications.

It is important to have a clear understanding of the distribution of spaces and technical installations within a building. This is obtained through the analysis of existing plans, combined with technical visits. It also facilitates the calculation of specific energy consumption for further comparison.

In Luxembourg, the regulation on energy efficiency defines the energy reference area as the conditioned portion of the net internal surface within the building envelope [74]. Nevertheless, given that certain benchmarks, such as those shown in **Table 2.2,** are based on gross floor area, the analyses in this study follow that convention. To ensure clarity, the reference areas used for the educational buildings are consistently specified.

Table 5.1 and **Table 5.2** present the evolution of the gross floor area and the heated gross floor area, respectively, for the four educational buildings over the analysed years. The data are based on architectural plans and on-site measurements. The difference between the total and heated floor areas is generally due to the presence of technical spaces that do not require heating. The values presented in the **Table 5.1** and **Table 5.2** consider all the buildings connected to the same central meter, even when they are not part of the same institution. This situation of a central meter serving to more than the analysed educational building is detected in buildings B and D. In the case of building B, the supplementary surface is considered, to allow a representative performance evaluation. Building D, counts with a local control of the third-party consumption, enabling the calculation of the local portion.

Table 5.1: Gross floor area evolution of the four studied educational buildings

Educational building	Gross floor area [m^2]							
	2017	2018	2019	2020	2021	2022	2023	2024
A	22,511	21,211	21,211	22,511	22,511	22,511	22,511	22,511
B	31,940	31,940	31,940	31,940	31,940	31,940	31,940	31,940
C	16,544	21,748	21,748	21,748	21,748	21,748	21,748	21,748
D	25,232	25,232	25,232	25,232	30,266	30,266	30,266	30,266

It is important to note that the buildings have undergone changes over the years, either due to renovation works or modifications in space usage. As a result, reference areas may also vary over time, and such changes must be carefully considered when analysing and comparing historical energy consumption. In this context, regular exchanges with stakeholders are essential to ensure the accuracy and relevance of the analysis.

Table 5.2: Heated gross floor area evolution of the four studied educational buildings

Educational building	Heated gross floor area [m^2]							
	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
A	18,654	17,354	17,354	18,654	18,654	18,654	18,654	18,654
B	23,480	23,480	23,480	23,480	23,480	23,480	23,480	23,480
C	14,559	19,763	19,763	19,763	19,763	19,763	19,763	19,763
D	24,660	24,660	24,660	24,660	29,694	29,694	29,694	29,694

In particular, the changes in the surface area of Buildings A and D are linked to the post-pandemic addition of new classrooms and the opening of a new canteen and sports hall, respectively. The swimming pool and the sports hall blocks of Building C were refurbished in 2017, and therefore they were not in use. Accounting for these variations in floor area across the years allows for a more accurate evaluation of building performance.

5.1.2. Occupancy

The public-school year in Luxembourg goes from September 15 to July 15. The schools are open for 36 weeks and closed for 16 weeks, with the following holidays distributed along this period, besides public holidays:

- All Saints Day holidays (one week);
- Christmas holidays (two weeks);
- Carnival holidays (one week);
- Easter (two weeks);
- Pentecost holidays (one week).

Building B follows a different schedule, where its activities are divided by semester. Teaching activities only stops at Christmas, Easter, and summer holidays. However, since this building also houses office-related activities, unoccupied periods are not clearly observed.

5.1.3. Energy vector

The data collection also includes the analysis of the energy vector used at each institution, as presented in **Table 5.3**.

Table 5.3: Energy vector used at each educational building

Educational building	Electrical energy	Thermal energy
A	Electricity mix in Luxembourg	Natural gas Heating oil (back-up)
B	Electricity mix in Luxembourg	District heating (mix between gas and wood pellets)
C	Electricity mix in Luxembourg Photovoltaic power plant (since May/2023)	District heating (mix between gas and wood pellets)
D	Electricity mix in Luxembourg Photovoltaic power plant (since Apr/2021)	Heating oil

5.1.4. Annual energy consumption

The energy performance of the buildings is derived from the analysis of consumption data, subsequent to verification and considering direct consumption from local renewable production. **Table 5.4** and **Table 5.5** presents the historical annual electricity and thermal consumption in MWh of each educational building from 2017 to 2024.

Table 5.4: Annual electricity consumption of the educational buildings

Educational building	Annual electricity consumption [MWh/a]							
	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
A	831	857	817	716	750	701	651	646
B	1,834	1,684	1,666	1,326	1,394	1,329	1,214	1,183
C	767	948	928	861	941	933	934	932
D	1,248	1,215	1,250	1,098	1,298	1,299	1,231	1,237

Over the historical period, Buildings A and B registered a reduction of 22% and 35% in the annual electricity consumption. Although Building C shows an increase in annual electricity consumption between 2017 and 2024, this is due to the fact that the block housing the swimming pool and sports hall was undergoing refurbishment in 2017 and was therefore not in use. Between 2018 and 2024 the consumption in the building presents a stable consumption, except from the year 2020, when all the buildings show a reduction in the yearly consumption due to the lockdown period during the COVID pandemic, followed by an increase in 2021 concerning the redistribution and extra ventilation measures to avoid new crisis. Building D also shows a constant electricity consumption over the historical period.

Table 5.5: Annual thermal consumption of the educational buildings

Educational building	Annual thermal consumption [MWh/a]							
	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
A	1,518	1,389	1,414	1,299	1,658	-	-	-
B	2,415	2,347	2,332	2,136	2,412	2,020	1,887	1,912
C	-	1,937	2,076	1,890	-	1,985	1,918	1,985
D	3,451	3,398	-	-	4,247	3,701	3,263	-

In terms of thermal annual consumption, the analysis of the annual consumption does not provide clear patterns, except from the influence of the lockdown reducing consumption, and the later increase of consumption due to the measures adopted in 2021, to avoid new cases of COVID.

Despite missing data for some years, an increase in thermal consumption at Building D is observed in 2021. This is partially due to new measures implemented to prevent another pandemic, but also because two new blocks housing a canteen and sports hall were inaugurated.

In 2022, due to the gas crisis, a reduction in the annual thermal consumption is also observed in Buildings B and D.

Figure 5.2 and **Figure 5.3**. present the yearly specific electrical and heat consumptions in kWh/m^{2}a, calculated from the division of the average value per building divided by the reference areas shown in **Table 5.1** and **Table 5.2**.

A general tendency of reduction of the specific electricity consumption is observed within the Buildings A, B and D from 2017 to 2024. Building C only shows a reduction in the specific electricity consumption in 2020, as per all the other buildings, due to the lockdown period during the pandemic. In 2021, Buildings A, B and C showed the retake of normal activities, although in the case of the tow first buildings, they do not reach the same consumption levels as before. Building B and Building D registered an expressive drop of the specific electricity consumption over the historical period. However, it must be noted that in the case of Building D this is due to the new and more efficient installations, and not necessarily due to an overall better performance.

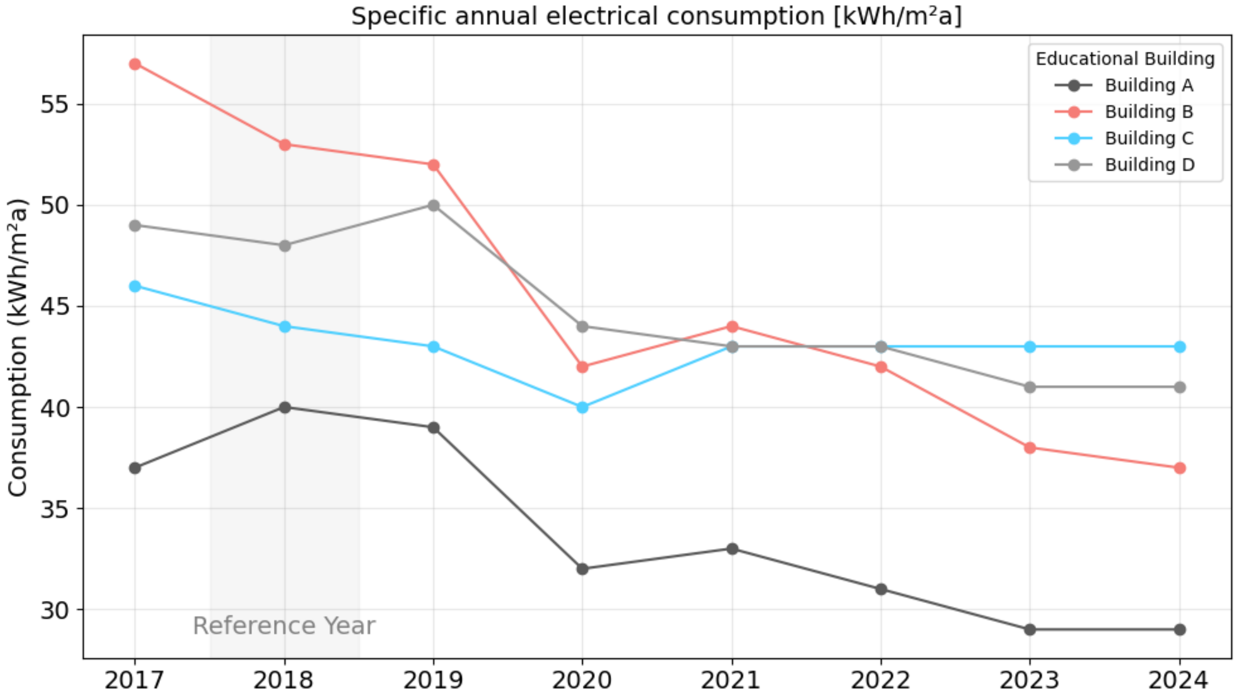


Figure 5.2: Specific annual electrical energy consumption from 2017 to 2024

It is important to highlight that although since Apr/2021 and May/2023, Building D and C, respectively, have photovoltaic installations, the analysed data refer to the actual consumption, including the local renewable production. Building D has monitoring data for both photovoltaic production and consumption, which makes it possible to evaluate the actual electricity consumption, including the part covered by self-consumption. The consumption data from building C, including self-consumption from the photovoltaic production, is obtained from the sum of the two main converters in the building that are monitored.

The data from heat consumption is not as complete as for electricity, due to available manual recording, however, from the analysis of **Table 5.5** and **Figure 5.3** it is possible to some patterns. Buildings A and B have shown a more or less stable specific thermal consumption over the years until the reduction in 2020, related to the lockdown period. Together with Building D, they also show an increase in 2021, referring to the higher air exchange rates imposed to reduce the propagation of COVID within the buildings. Furthermore, a tendency of reduction is observed in 2022 and 2023, due to measures related to the energy crisis, especially observed in Building D. As per Building C a similar pattern is observed for the five years of available data.

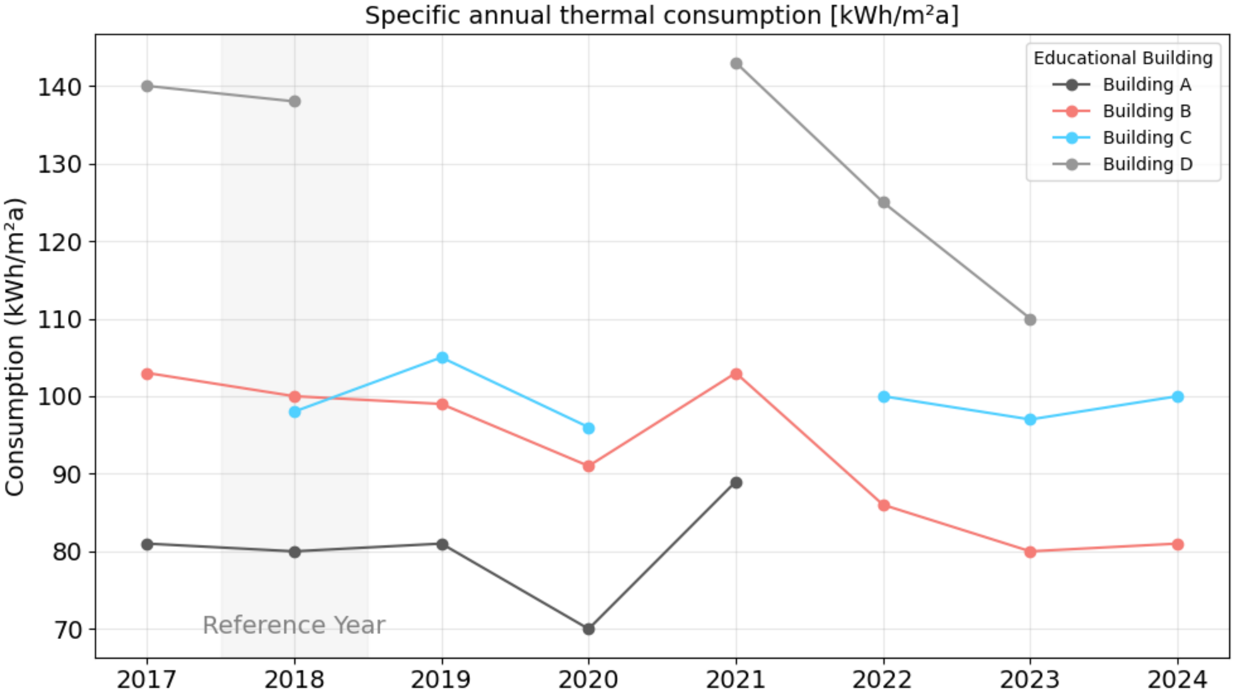


Figure 5.3: Specific annual thermal energy consumption from 2017 to 2024

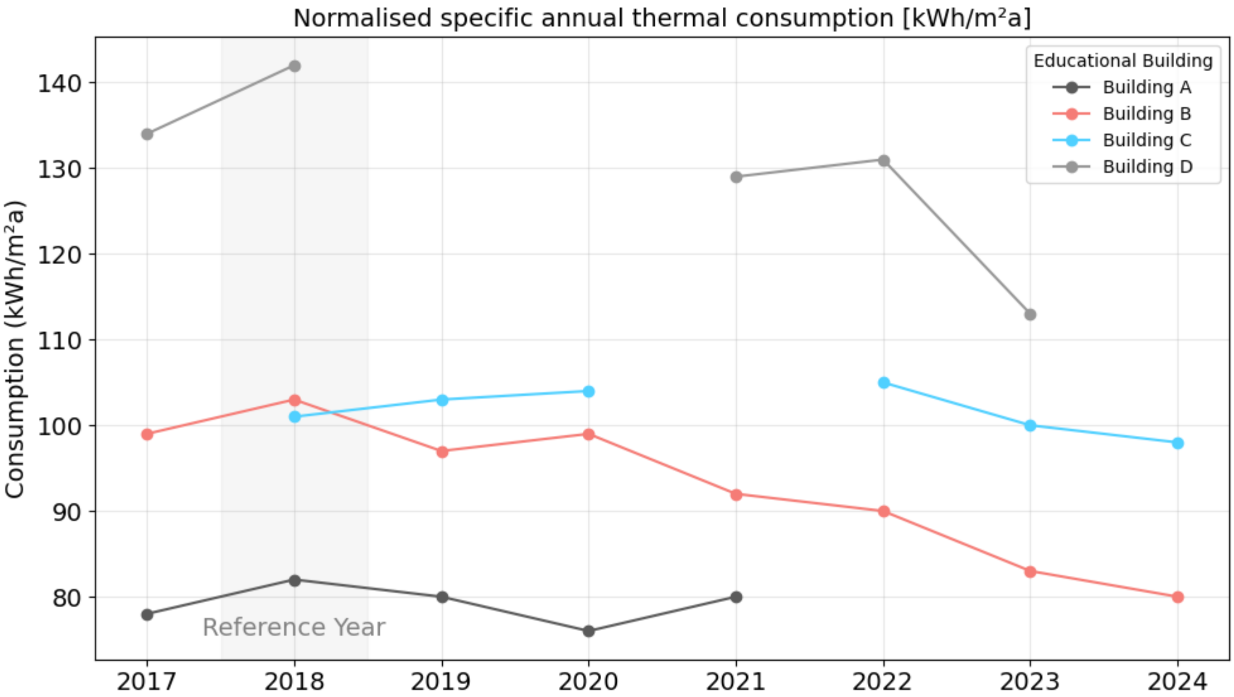


Figure 5.4: Normalised specific annual thermal energy consumption from 2017 to 2023

For a better evaluation of the consumption tendencies over the years, and to neutralise the impact of meteorological conditions on the thermal consumption variation, **Figure 5.4** present the normalised specific annual thermal energy consumption from 2017 to 2024. The analysis of **Figure 5.4**, shows a stable normalised specific thermal consumption patter for Building A and C. When considering the yearly meteorological influence on thermal consumption, a 20% reduction is observed in Building B over the historical period. A reduction of 16% between 2017 and 2023 is also observed in Building D.

5.1.5. Comparison with local benchmarks

The comparison between specific consumptions provides a better overview regarding the energy performance of the buildings for the reference year, in this case the consumption registered in 2018. Comparing the information specific electricity consumption of the reference year, with the reference benchmark in **Table 2.2**, shows that the four buildings consume more than the local average for similar buildings, as it can be observed from **Figure 5.5**.

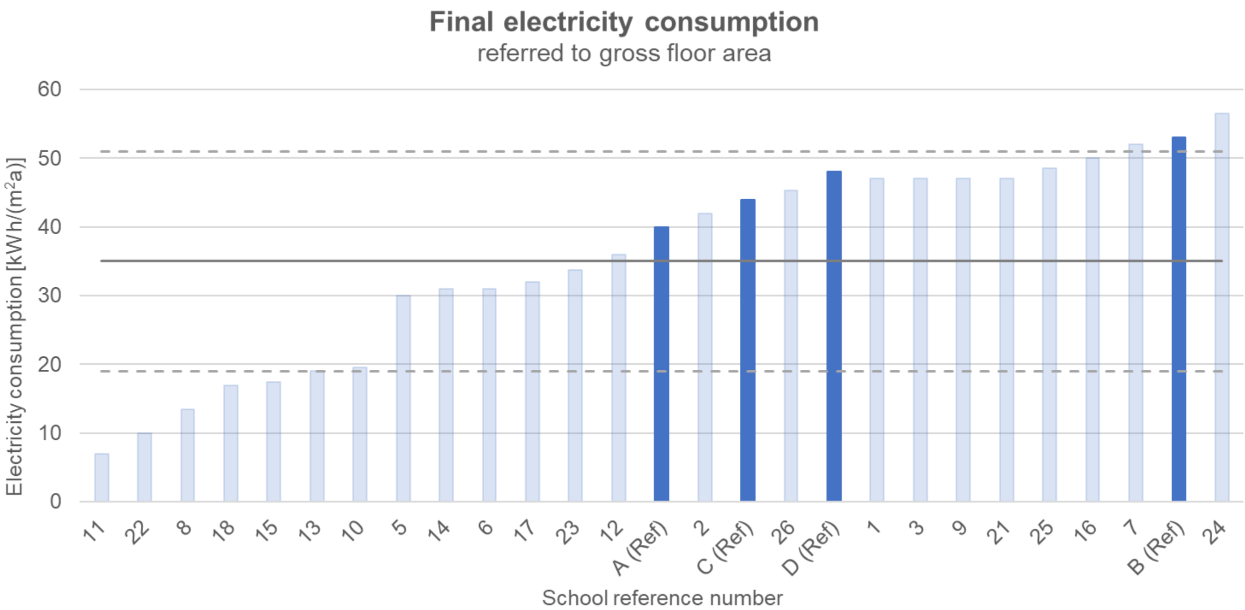


Figure 5.5: Final specific electricity consumption of four analysed buildings (dark blue) in comparison to 24 similar buildings in Luxembourg (Based on [25]*)*

The comparison of the specific thermal consumption of the four buildings in the reference year, with the reference benchmark in **Table 2.2** shows that all four studied buildings consume less than the local average.

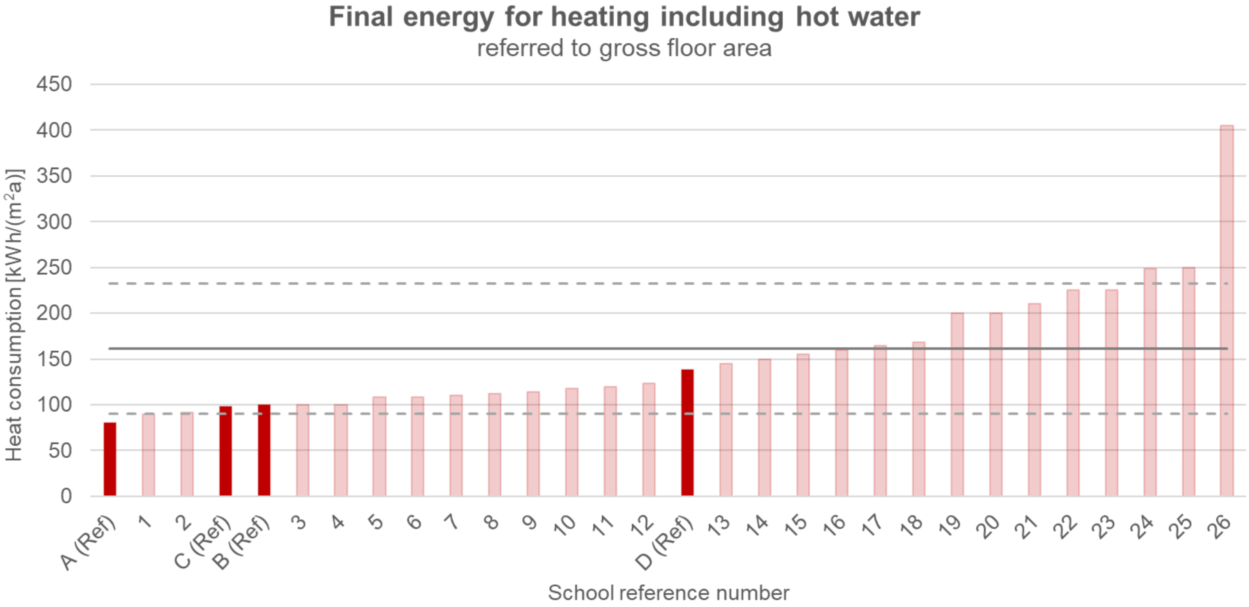


Figure 5.6: Final specific heat consumption of four analysed buildings (dark red) in comparison to 26 similar buildings in Luxembourg (Based on [25]*)*

Following the flowchart presented in **Figure 5.1**, the analysis regarding the energy performance of buildings highlights the areas where efforts should be focused to identify potential energy savings. For the studied buildings, greater opportunities appear to lie in reducing electrical consumption rather than thermal. This suggests that a more detailed investigation of electricity use is justified. At the same time, the above-average performance in heat consumption compared to national benchmarks does not imply the absence of further energy saving potential. A comprehensive analysis of overall energy use remains essential.

5.2. Electrical energy consumption analysis

Over the years, with the energy efficiency regulations there has been a tendency to transition from thermal energy to electrical appliances, therefore increasing the overall electricity consumption. Besides the increasing comfort-related techniques, together with the growing adoption of educational technologies, prevent further reductions in consumption. In order to identify potential energy savings, the electricity consumption data obtained from the combination of the historical together with the local measurements are analysed regarding their patterns and distribution among types of use.

5.2.1. Consumption patterns

The analysis of consumption data offers insights into the manner in which energy is consumed within a building during specific periods. A comparison between total annual consumption over the years provides information about the tendency for overall variation.

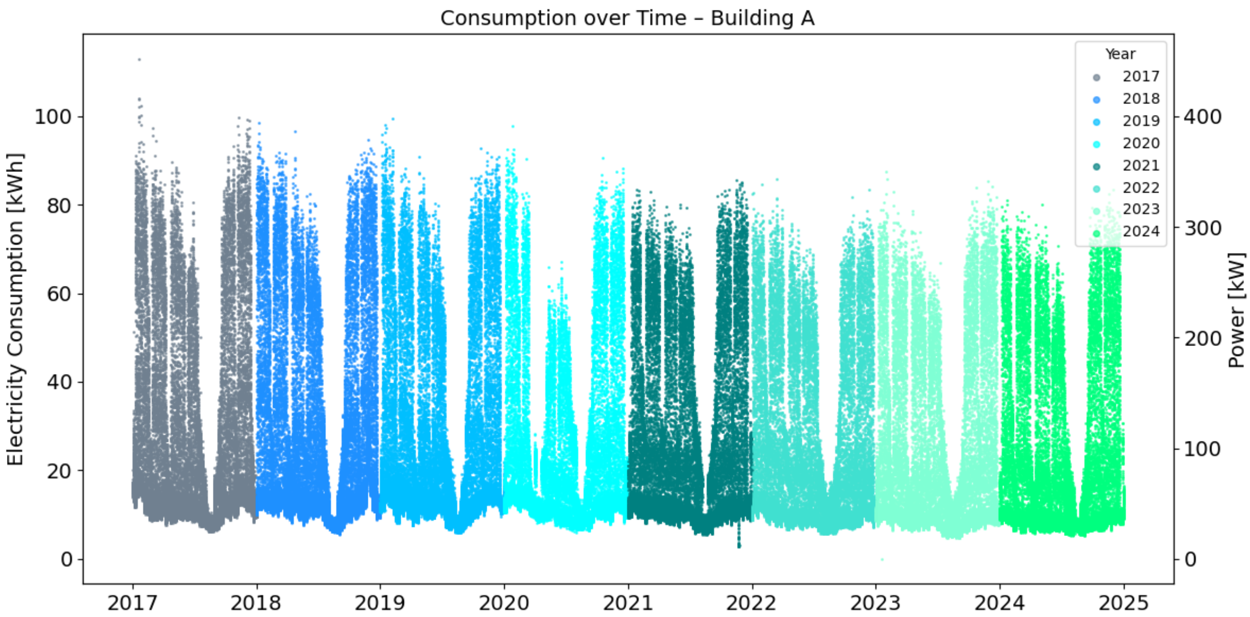


Figure 5.7: Electricity consumption data over the years (Building A)

The analysis of shorter intervals provides a detailed understanding of the specific periods during which changes occur. In the example presented in **Figure 5.7**, where 15-minute consumption data is plotted over the years, a significant reduction is perceived at the peak, whereas the baseload consumption does not expressively vary over the years.

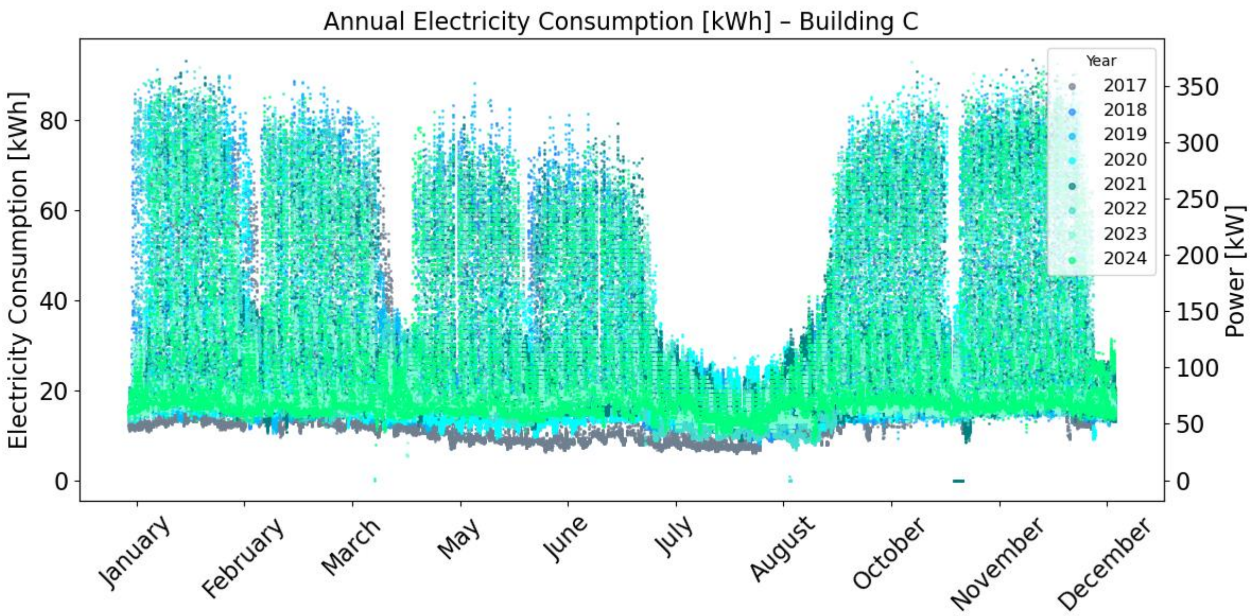


Figure 5.8: Electricity consumption data over the years (Building C)

Furthermore, the superposition of the 15-minute consumption data for the analysed years shows a clear consumption pattern related to the school calendar. **Figure 5.8** displays the similar patterns over the year, where the weekends and school breaks are clearly marked by a reduced consumption. It is also clear that the baseload consumption of Building C increased since August 2017.

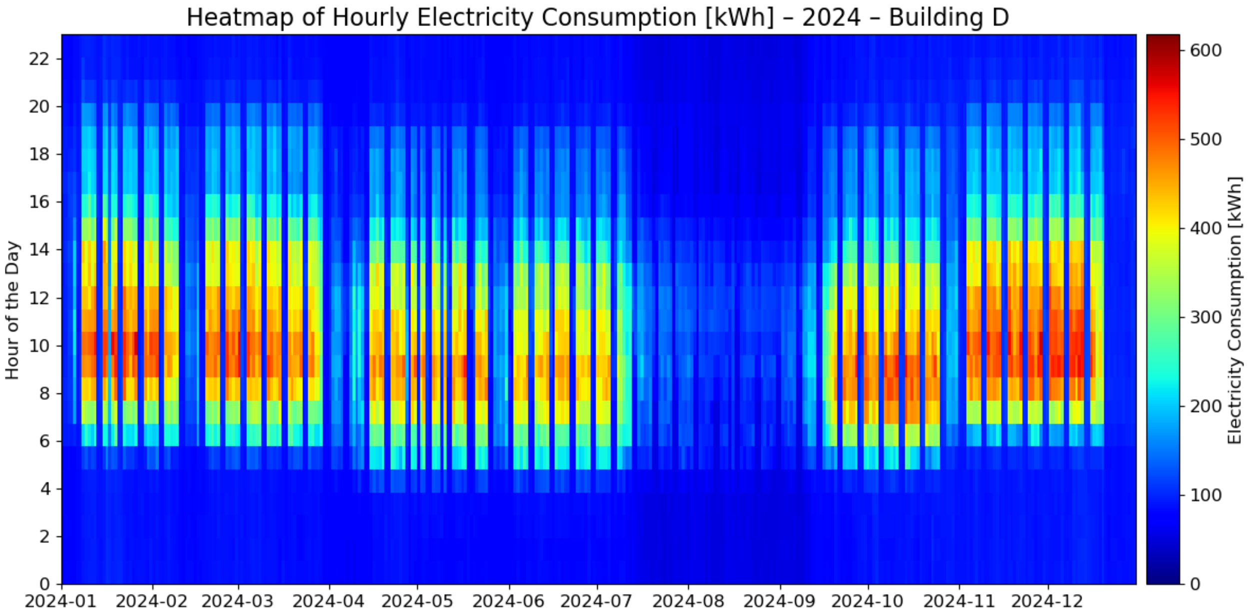


Figure 5.9: Electricity consumption data over the years (Building D)

The heatmap in **Figure 5.9** illustrates the hourly electricity consumption trends throughout the year 2024. The noticeable one-hour shift in the consumption pattern is a result of daylight-saving time, during which clocks are set forward by one hour during the summer months. Weekday activity is clearly reflected, with daily activities beginning around 6h00 CET (5h00 CET during the summer), and the peak consumption levels typically occurring between 9h00 and 10h00 CET (8h00 to 9h00 CET in summer), following the occupancy profile of the building. Most teaching activities conclude around 14h00 CET (13h00 CET in summer). Periods of low occupancy, such as weekends and holidays, are marked by significantly lower consumption levels, with usage peaks mostly occurring in the morning hours of working days. Seasonal weather effects are also evident, with higher consumption peaks observed during the heating periods at the start and end of the year, and a noticeable decline as the summer approaches.

The contrast in consumption patterns throughout the year becomes even more evident in **Figure 5.10**, which presents a comparison of four distinct weeks across the annual cycle, two representing typical activity and two corresponding to holiday periods, each taken from both the summer and winter seasons. Normal weeks are shown in red, while holiday weeks appear in blue. The consumption data analysis highlights the significant influence of both building occupancy and weather conditions on electricity use.

The analysis confirms that user presence is the predominant driver of electricity consumption in Building C, especially when contrasting holiday periods with regular operational weeks. Comparing typical winter weeks (shown in darker tones) with summer weeks (shown in lighter tones) further illustrates the impact of seasonal climatic variation on energy demand.

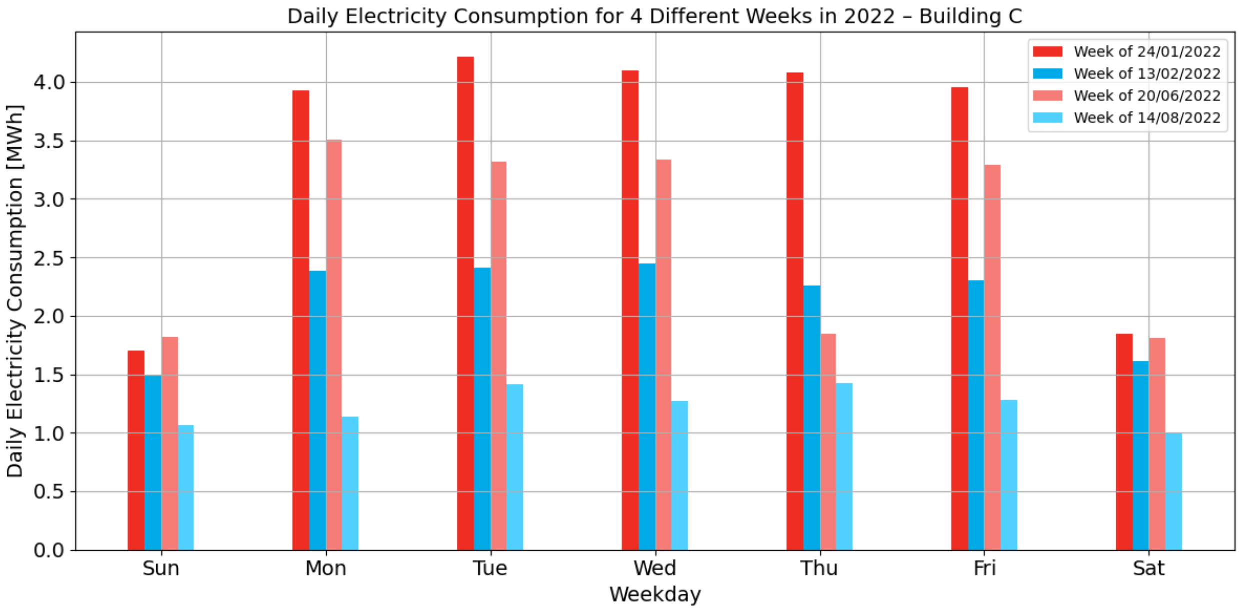


Figure 5.10: Daily electricity consumption during four typical weeks (Building C)

The lowest levels of electricity consumption levels are consistently observed during weekends, highlighting the influence of user presence and the programmed operation of technical systems on the energy usage of the building. Notably, the minimum consumption is recorded during the summer holiday period (week of 14/08/2022 – shown in light blue), emphasizing the additional effect of meteorological conditions. This is particularly evident when contrasted with winter low-occupancy periods (week of 24/01/2022 – shown in dark blue), where energy use remains comparatively higher.

Despite being unoccupied during holiday periods, the electricity consumption of the building in winter exceeds that in summer. In both seasons, weekday consumption is higher than at weekends, with the difference being more pronounced during the colder months. This suggests that systems may continue to operate based on preset schedules in the absence of occupants, indicating considerable potential for reducing energy use without affecting comfort levels. Following the flowchart presented in **Figure 5.1**, the deviations identified in the consumption patterns indicates where to effectively concentrate efforts to reduce energy consumption. Further analysis is needed to determine the extent to which these savings can be realised effectively.

5.2.2. Baseload consumption

The consumption which happens when the building is empty is analysed following the methodology presented in **3.4.2 Electricity consumption analysis**. The elbow point of the yearly duration line indicates power load below which baseload is occurring, which allows to define the consumption occurring during this period, using **Equation 3.3**.

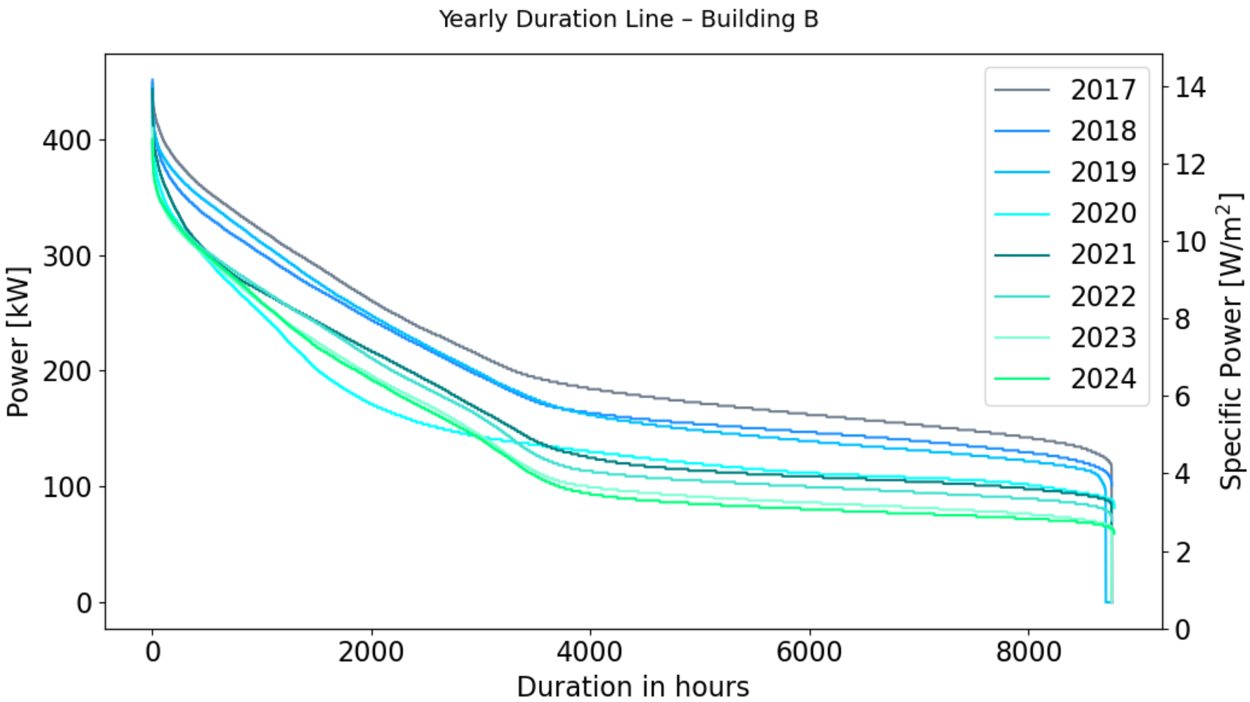


Figure 5.11: Yearly distribution line of the power requirements (Building B)

Figure 5.11 shows a gradual decline in both peak power demand and, more significantly, in the baseload over the years, which has directly contributed to the overall reduction in electricity consumption. Over the past seven years, the annual baseload consumption has decreased by approximately 50%. A particularly significant drop is evident between 2019 and 2020, with two other noteworthy reductions occurring between 2021 and 2023. These trends are linked to the decommissioning of highly inefficient mechanical ventilation systems in certain sections of the building, as well as the relocation of servers to another facility during the 2016–2023 period.

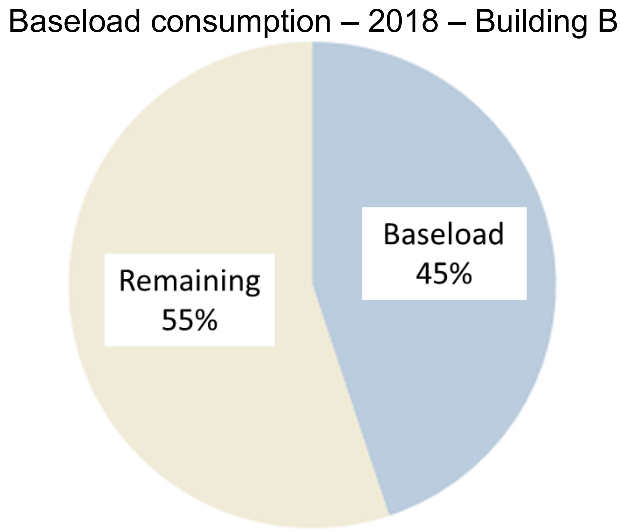


Figure 5.12: Baseload consumption – period 2018 (Building B)

As illustrated in **Figure 5.12**, electricity consumption during unoccupied periods in Building B accounts for nearly half of the total energy use over the historical timeframe analysed, highlighting significant opportunities for energy savings during these times. The results point to the potential effectiveness of strategies specifically targeting consumption during unoccupied periods.

5.2.3. Consumption distribution

Buildings A, C and D have two sets of electric meters installed to monitor sub-sections of the building or technical installations with an important energy demand providing information for the distribution of the energy consumption.

Building B has one central meter serving six different building blocks. Three blocks are equipped with sub meters, as well as the server room and its dedicated cooling system. For further analysis, of the consumption distribution requires local mobile measurements.

Building B

The analysis of energy consumption in Building B is focused on the Central Building. To analyse the distribution of electricity consumption in the Central Building by type of use, it is first essential to identify all consumers connected to the main electrical cabinet. This step is necessary due to the complexity of the building, as it comprises multiple structures with distinct physical characteristics, technical systems, and activities.

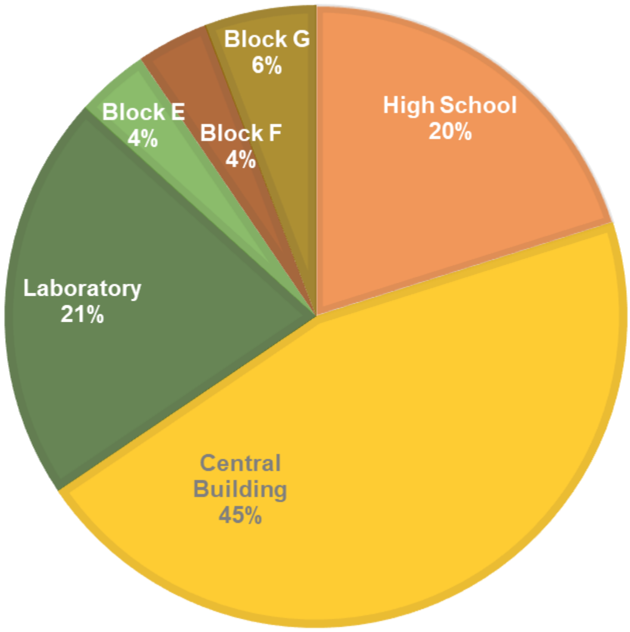
Building B only has a central meter, which is also feeding the five blocks composing the complex of buildings – Central building, Laboratory, block E, block F and block G – and another high-school building – HS – which is not concerned in this analysis. The reference gross floor area distribution within the six blocks of buildings is presented in **Table 5.6**.

The first step of the analysis in this case is to quantify the electricity consumption corresponding to the high school building, which is not part of the complex of buildings, herewith called Building B. The consumption measured using local meters, is deduced from the overall values obtained from the energy management system, from **Table 5.4**.

Until November 2024, there was no separate meter for the cabinet serving the high school, which was not accessible for local measurements. The consumption was estimated according to their characteristics and use pattern.

Table 5.6: Reference gross floor area of the building blocks composing Building B

Building B	Gross floor area [m²]
Central Building	14504
Laboratory	6760
Block E	1196
Block F	1841
Block G	1210
High School	6429



The high school building is a simple pavilion, built in the year 1999, with an extension from 2020, heated by a gas boiler, with no centralised mechanical ventilation. It is mainly dedicated to classrooms, which represents 53% of the surface area, where 4% is dedicated to cooking classes. The common areas and hallways represent 26% of the total surface area. Offices and a small canteen represent further 6% each, of the total surface area, while the remaining 9% are dedicated to a library and storage rooms. Only 7% of the building is equipped with mechanical ventilation. Although it counts with a canteen, the building is not equipped with special laboratories, or consuming equipment, further than the necessary in normal classrooms. Furthermore, it does not have sports hall and swimming pool.

According to the latest energy certificate, from the year 2024, the high school building has a simulated specific electricity consumption of 17 kWh/m^2. The analysis of local high school building consumptions developed by Thewes et al., (2014), shows an average consumption of 21 kWh/m^2 between the five standard buildings with canteen, presenting electricity consumption below 26 kWh/m^2 (average for school buildings with canteen, without accounting for their impact in the consumption). This serves as validation to use the energy certificate value in further calculations [79]. Finally, the local measurements realized between November 2024 and July 2025, show an extrapolated yearly consumption of 193 MWh/a for the building, which represents 30 kWh/m^2. This information is used in further calculations.

Blocks E, F and G are equipped with separate meters, where similar specific consumptions are measured for these three blocks, explained by their similar characteristics and use patterns. The specific consumptions obtained for Blocks E, F and G are 26, 21 and 26 kWh/m^2, respectively.

These four building blocks present relatively specific low consumptions when compared to Central Building and Laboratory, which from the above presented information, is calculated as 82% of the consumption registered in the energy management system in 2022. These two buildings are assumed to have a similar electricity consumption, except from the presence of a server room in Central Building.

As of 2022, the Central Building has a separate meter to measure the electricity consumption of the server room. The electricity consumption of the cooling system supplying the server room is measured independently, as shown in **Table 5.7**.

Table 5.7: Electricity consumption of server room - Building B

Electricity consumption [MWh]	2022	2023	2024
Servers	*137*	*93*	*74*
Dedicated cooling	*114*	*96*	*77*
Server room	**251**	**189**	**151**

The distribution between Central Building and Laboratory is obtained by deducing the consumption of a server room, and dividing it by their surface areas. The average specific consumption of these two building is 35 kWh/m^2.

The distribution between Central Building and Laboratory is obtained from multiplying the specific consumption by their surface areas. The final share of the Central Building also includes the electricity requirement of the server room. This represents specific consumption of 52 kWh/m^2 in 2022, which is 48% higher than the national average reference for the electrical consumption in educational buildings, from in **Table 2.2**.

The distribution of the overall consumption per building block is shown in **Figure 5.13**. The separation between Central Building and Laboratory presented in **Figure 5.13**, as already mentioned, only refers to the server room, and the different reference gross floor areas for the two blocks, given in **Table 5.6**. Further repartition requires local measurements.

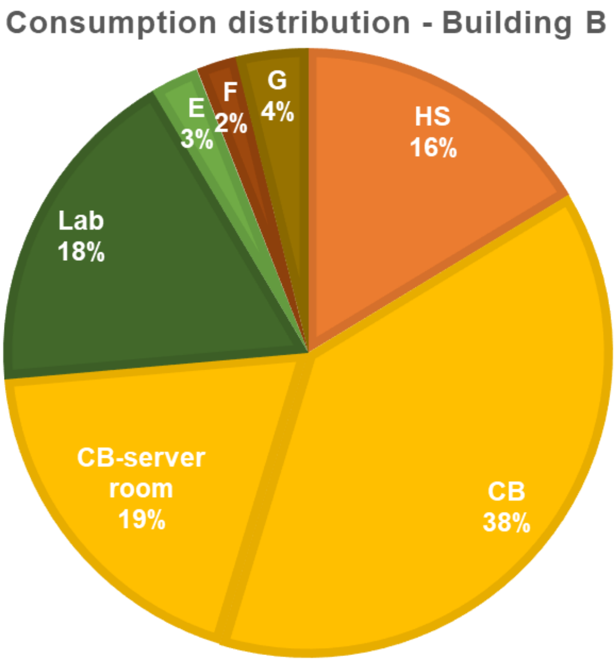


Figure 5.13: Electricity consumption distribution within blocks High school (HS), blocks E, F and G, Laboratory (Lab) and Central Building (CB + CB-Server room) in 2022

The analysis of the specific consumptions per building block highlights that only Central Building and the Laboratory exhibit consumptions above the national average. Following the energy audit flowchart from **Figure 5.1**, further analysis concerning the distribution of the electricity consumption, to allow the identification of energy-saving opportunities, is focused on the Central Building, since it represents alone 57% (38% Central Building and 19% Server room) of the overall recorded consumption.

The further analysis of the electricity consumption distribution at the Central Building focuses on the mechanical ventilation system, the above mentioned the server room, and the lighting.

The Central Building has six air handling units, serving three auditoriums, a conference room, a canteen and a kitchen. The mechanical ventilation of the three auditoriums has been discontinued since the year of 2021. The other three operating systems are presented in **Table 5.8**, and their consumption is measured in April/2023, with a mobile device, following the methodology described in **3.3.3 Energy consumption**.

During the measurements, it was observed that although the system serving the conference room should only operate under request, in April/2023 while the space was not being used, the air handling unit was operating at full capacity, leading to a yearly consumption of 10 MWh. This represents almost the same amount as the two other systems, serving the kitchen and the canteen together. This highlight how a simple energy audit can reveal significant opportunities for energy savings that require minimal effort to implement.

Table 5.8: Air handling units - Building B in 2023

Air handling units	Conference room	Kitchen	Canteen
Nominal capacity supply/exhaust [m^3/h]	16000/16000	4500/4500	7000/7000
Operating schedule	Only when required	05:30h – 18:30h	05:30h – 15:30h
Yearly electricity consumption [MWh]	10	5.5	4.2

The analysis of the lighting system shows a mixture between different devices, showing that gradually there is a shift from older and inefficient systems, towards less energy demanding ones. Over the years the building has passed for many small renovations, comprising the replacement of the lighting system, even coupled with presence sensor for common areas.

Local measurements showed that most of the classrooms and common areas presented installed power corresponding to 30 kWh/m^2a in the year of 2022, which corresponds to the references for ancient systems from Thewes (2011) [72]. Other parts of the building such as auditoriums and offices present almost half of the installed power, leading to specific consumptions closer to 15 kWh/m^2a, matching the references for newer devices, without presence sensors [72]. Considering that common areas and the classrooms represent around 50% of the surface area of the Central Building, a 19 kWh/m^2a is adopted to identify the portion of electricity consumption referring to the lighting.

The distribution of the electricity consumption in the Central Building of Building B, in 2022 is presented in **Figure 5.14**. From the analysis of the distribution, it is clear that lighting plays an important role in the total electricity consumption. This is mainly due to the long operational hours of low efficiency systems, specially concerning over illuminated common areas, and corridors, which in 2022 operated for 14h/day during weekdays.

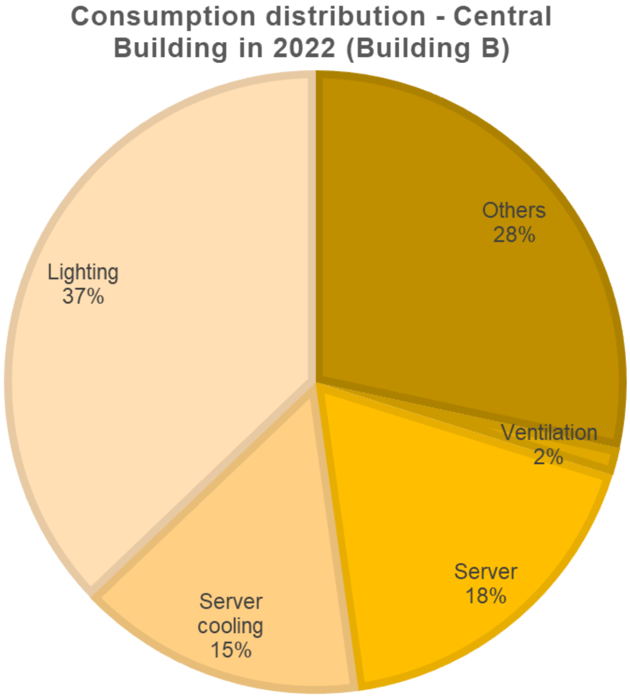


Figure 5.14: Electricity consumption distribution of Central Building in 2022 (Building B)

The evolution of the electricity consumption distribution of the Central Building is analysed between the years of 2022 and 2024, as presented in **Figure 5.15**. It is possible to verify an overall reduction of 14%, where lighting represented 27% of the reduction over the years. The consumption related to the server room (composed of the servers and the dedicated cooling) contributed to the further reduction of 73%, due to relocation to another building.

The reduction observed in the lighting over the last years refers mainly to the revision of the illuminance levels of common areas in the building, combined with a reduction in their operational hours. Local measurements of the illuminance at the corridors showed rates above the 50 lx to 100 lx recommended for circulation and common areas by the local norms [113]. The observed energy savings were obtained by adapting the lighting system to attain 100 lx in common areas, while the operational hours were reduced. These measures, combined with small renovations and gradual replacement of old devices led to the reduction of the consumption to 17 kWh/m^{2}a.

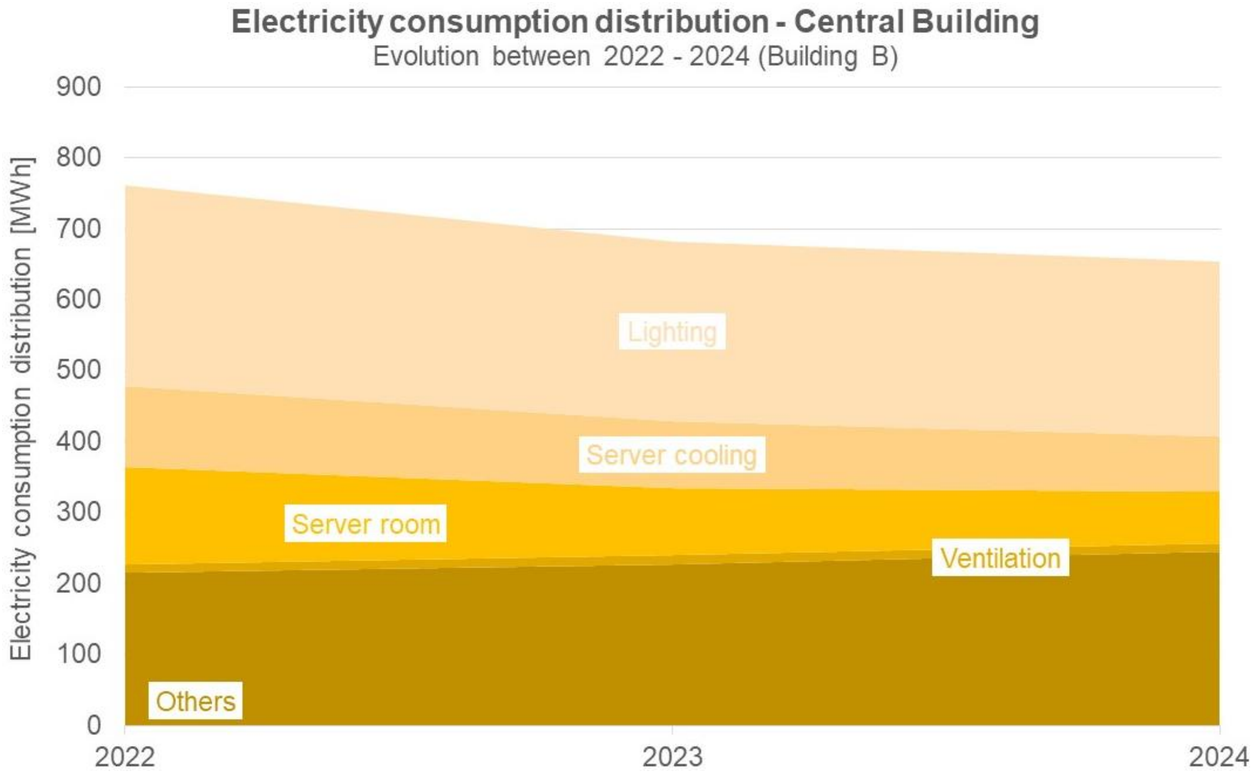


Figure 5.15: Electricity consumption distribution of Central Building – Evolution between 2022 and 2024 (Building B)

The reduction regarding the server room is justified by the relocation of parts of various servers and dedicated cooling to another building. The moving process happened between 2016 and 2023.

The full operation of the mechanical ventilation system in the conference room when not needed could have doubled the electricity consumption during. Since the issue was identified the energy management staff was notified to fix it.

An increase of 10% between the years of 2022 and 2024 is observed in the category referring to the unspecified portion of the electricity consumption of Central Building. These unspecified consumers are composed by technical equipment, such as circulator pumps for the heating systems, or by appliances, such as computers, printers, beamers, and laboratory equipment. Over the three last years an increase in the number of people allocated in the Central Building has increased, which could justify the change observed in the electricity consumption category.

The analysis of the energy consumption distribution serves as a reference for both planning interventions and controlling their impact afterwards.

Building C

The electricity consumption of Building C is measured and categorised according to various types of use. Analysing consumption by these categories enables a clearer identification of the systems and activities that are the most energy-intensive. Following the energy audit flowchart presented in **Figure 5.1**, systems with higher energy demands are examined in detail to assess their performance and to identify specific opportunities for energy savings.

Figure 5.16 illustrates the distribution of electricity consumption in Building C during the year 2023. Based on the analysis of the main electrical cabinets, six major consumers were selected for monitoring, following the methodology described in Section **3.3.3 Energy consumption** and **Annex III**. The data collected from these monitored systems was subtracted from the total consumption from the energy management system, resulting in the initial consumption breakdown shown in **Figure 5.16 (a)**. However, this first step still left more than 50% of the total energy consumption unaccounted for.

To refine the distribution, additional local and temporary measurements were conducted on specific installations. These measurements, together with estimations based on equipment power ratings and operational hours, were used to generate the breakdowns shown in **Figure 5.16 (b)** and **(c)**.

From **Figure 5.16 (b)**, it is evident that lighting systems and digital devices represent a significant share of the total electricity consumption. Although lighting systems have progressively become more energy-efficient in recent years, the increased use of digital equipment in connected classrooms has offset some of the expected energy savings. This limits the observable impact of the lighting upgrades on overall energy consumption.

A separate building within the school complex houses the sports hall and the swimming pool. As shown in **Figure 5.16 (a)** and **(b)**, this section alone accounts for approximately one-third of the total electricity use. It includes facilities such as a swimming pool, sports court, changing rooms, showers, and a dedicated technical area located underground. **Figure 5.16 (b)** identifies this area as the highest energy consumer, justifying the need for a more detailed assessment. The specific consumption breakdown for this part of the building is presented in **Figure 5.16 (c)**, where the water treatment pumps and the heating circulators are shown to be the most energy-demanding appliances.

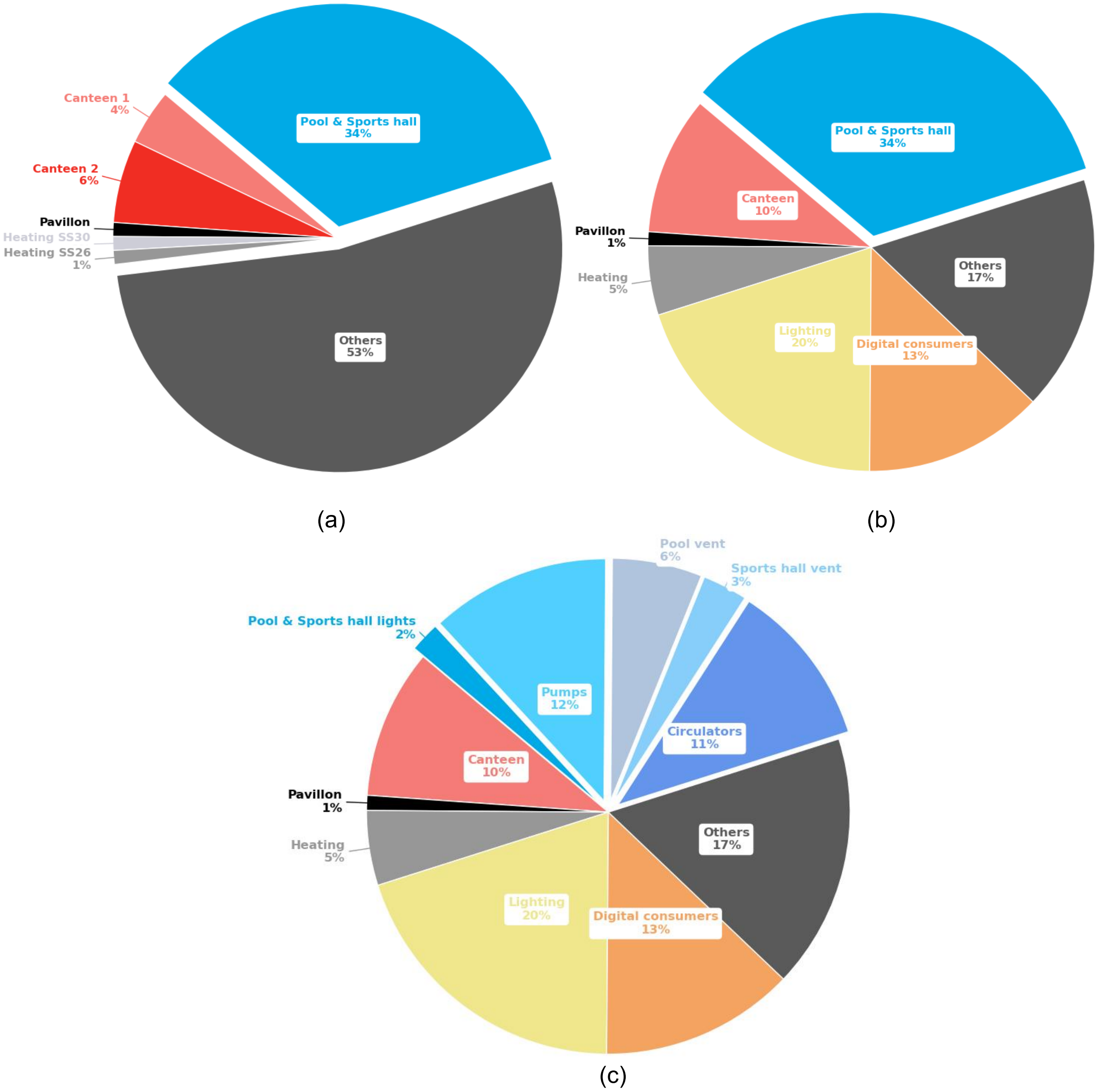


Figure 5.16: Distribution of the electricity consumption in 2023 - Building C: (a) First set of big consumers; (b) Redistribution of the “Others” category; (c) Redistribution of the swimming pool and sports hall, in 2023

The results of the energy audit serve as a guide to the intervention strategy, enabling energy savings without compromising comfort, by focusing on reduced operational modes during unoccupied periods and implementing targeted sufficiency measures. The audit also helps identify and correct deviations in the operation of technical installations to prevent unnecessary energy consumption while ensuring they operate according to requirements. In the case of the studied buildings, Building B focused on the savings related to the reduction of the baseload consumption and the lighting in common areas. As per Building C, the focus is set on the operation of the pumps at the swimming pool.

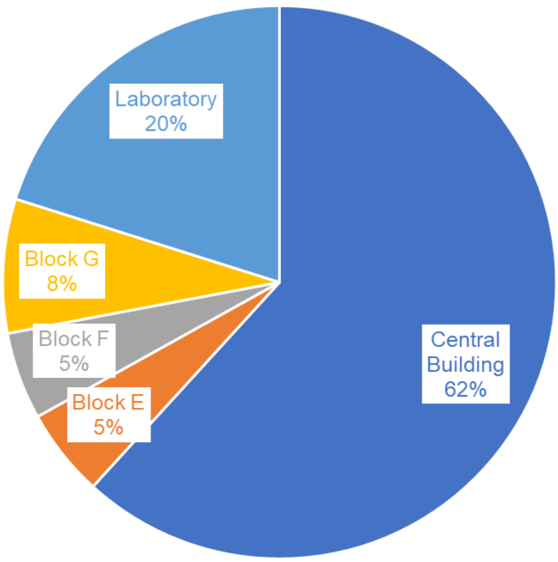
5.3. Thermal analysis

Following up on Step 2 of the framework presented in **Figure 3.1**, referring to the energy audit, and the flowchart presented in **Figure 5.1**, this subchapter shifts the focus from electricity to thermal energy consumption. After identifying opportunities related to electricity use, the next step is to explore potential improvements in thermal energy performance across the studied buildings.

The analysis of thermal energy consumption is carried out following the methodology described in **3.4.3 Thermal consumption analysis**. The focus is placed on Building B, which recorded the second highest specific thermal consumption in 2018, and has available data for detailed evaluation. The thermal model of Building B is developed using LESOSAI software, drawing on architectural plans and complemented by on-site measurements.

Table 5.9: Heated gross floor area of the buildings in Building B

Building B	Heated gross floor area [m^2]
Central	14504
Laboratory	4726
Block E	1210
Block F	1196
Block G	1841



The analysed campus is composed of a complex formed by five different independent blocks, here identified as Central building, Laboratory, block E, block F and block G. Among the five existing blocks, two (Central Building and Laboratory) date from the original construction period in the early seventies, while the other three were built in a later stage, thus they are more modern, and have different building components. The three new blocks (E, F and G) are used as offices, while the two older are composed by a mixture between classrooms, laboratories and offices.

This analysis focuses on the two main blocks, with similar characteristics and built in the same period, here called Central building and Laboratory. Therefore, the overall consumption obtained from the central meter, presented in **Table 5.5** is separated per block. Two of the three new blocks (F and G) are equipped with sub meters, allowing for the extrapolation of the consumption of block E, since this is very similar in components, shape and usage to block F. As per Central Building and Laboratory, considering that both have the same components, it is assumed that they present similar specific thermal losses and heating requirements, and are analysed together.

Table 5.10: Annual thermal consumption distribution within Building B, and specific consumption in the reference year (2018)

Building B	Annual thermal consumption [MWh/a]								Specific consumption [kWh/m²a]
	2017	2018	2019	2020	2021	2022	2023	2024	
Central + Lab	2,169	2,108	2,095	1,918	2,167	1,815	1,695	1,717	**110**
Block E	75	73	73	66	75	63	59	62	**60**
Block F	75	73	73	66	75	63	59	62	**61**
Block G	96	93	92	85	96	80	75	79	**51**

The distribution of the heating energy consumption measured at the central meter (**Table 5.5**) of Building B is presented in **Table 5.10**. This distribution is obtained from the sub meters in blocks F and G, and the extrapolation for block E.

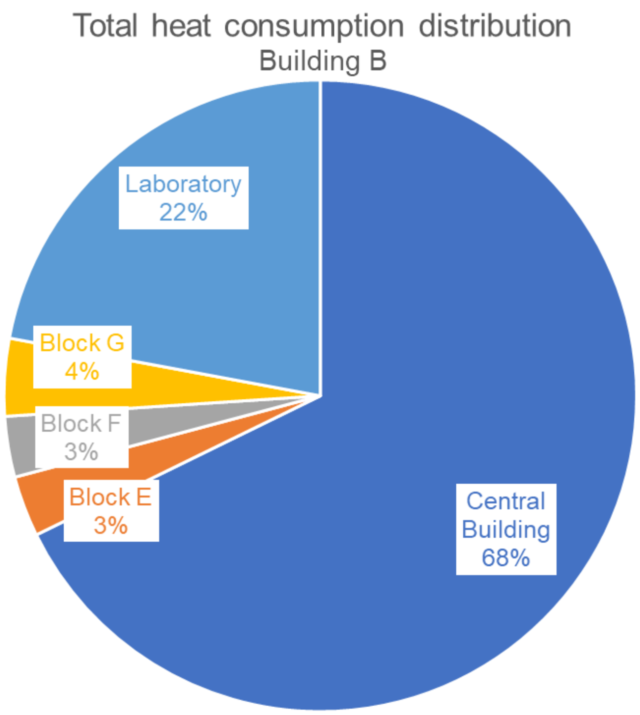


Figure 5.17: Total heat energy distribution within the five blocks composing Building B

The heat consumption distribution per building block is presented in **Figure 5.17**, and it is obtained from the values presented above, in **Table 5.10**, and the repartition between the Central Building and Laboratory, considering their reference area.

The thermal model of Building B, is developed based on the following information:

- Climate data: Luxembourg 2008 (Government LESOSAI)
- Internal gains: It is calculated considering the number of people in the building, the duration of the occupation, and their metabolic activity, in this case corresponding to sitting position.
- Heating system:
    - Efficiency of the heating system: 85% [25], only considering internal heat distribution, emission and control losses since the heat is delivered by district heating. These account for losses in pipes, heat exchangers, substations, valves, circulator pumps and the heterogeneous losses happening behind the radiators, where higher temperatures are observed.
    - Required temperature:
        - 20°C – for classrooms, laboratories, offices, and common areas

          The controlling valves of the radiators in classrooms and offices are fixed in position 3, which corresponds to around 20°C. However, it must be highlighted that the central managements system adapts the internal required temperature according to the external temperature. The monitoring shows that the measured temperature in classrooms, where the radiators are centrally controlled reaches the 20°C, used in this analysis, only increasing due to solar or internal gains, related to the presence of students and staff.

        - 16°C – for corridors

          The controlling valves of the radiators placed at the corridors in the central building are set-up in position 2, corresponding to around 4°C less than position 3.

    - Heating schedule:
        - The heating system is centrally controlled to provide:
            - 20°C between 5:00h and 18:00h, on Mondays
            - 20°C between 6:00h and 18:00h, from Tuesdays to Saturdays

- 16°C during the night and on Sundays

In the thermal model, the reduced heating mode is applied to the entire building and it considers a duration of 8h per weekday, and 62h over the weekend. In both modes the minimum internal temperature is defined as 16°C.

  - Domestic hot water: it is estimated based on the number of prepared meals at the kitchen.
- Mechanical ventilation: Only in three rooms:
  - Kitchen:
    - supply and exhaust rates: 4500 [m³/h] / 4500 [m³/h]
    - operating hours: 13 h/d
  - Canteen:
    - supply and exhaust rates: 7000 [m³/h] / 7000 [m³/h]
    - operating hours: 10 h/d
  - Conference room:
    - supply and exhaust rates: 16000 [m³/h] / 16000 [m³/h]
    - operating hours: only on demand ~ 350 h/year
- Building components and their characteristics:
  - Thermal bridges: as standard
  - Air tightness of the building:
    - n_{50} = 4.36 1/h (areas with mechanical ventilation)

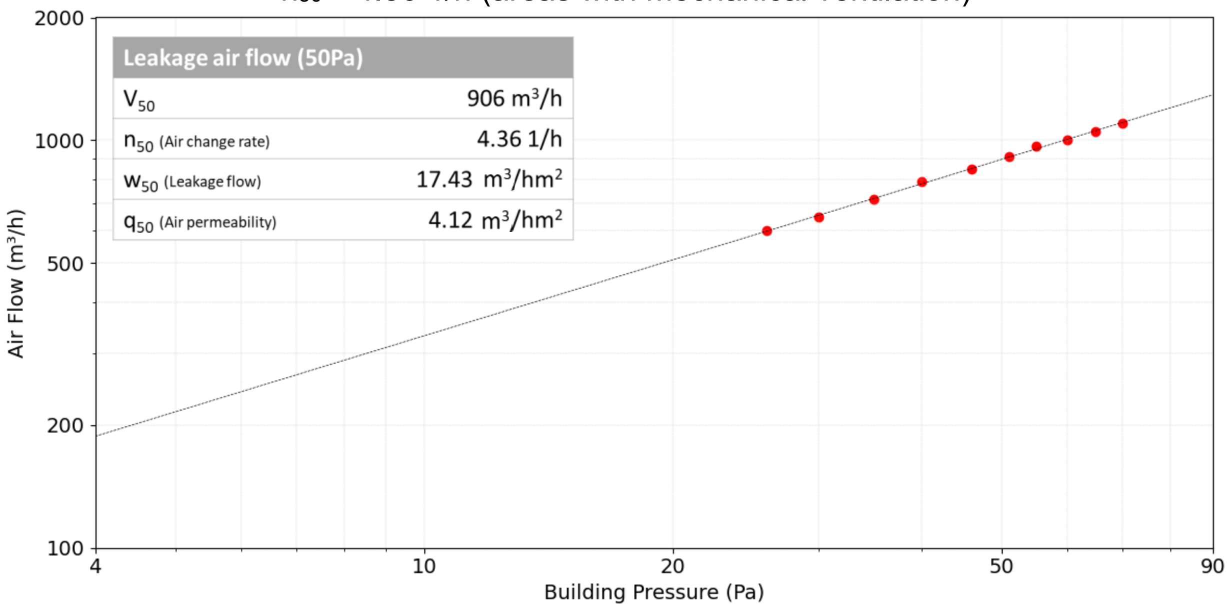


Figure 5.18: Results from the blower door test – Central building (Building B)

- $n_{n_{50}}$ = 0.7 1/h (areas with mechanical ventilation)
- n = 0.3 1/h (areas with natural ventilation)

The air tightness of the building is defined based on the blower-door test measurements realised following the methodology presented in **3.3.4 Building physics**. The initial n_{50} value adopted in this analysis refers to the results of the blower-door test measurements realised in one representative room, with similar characteristics to the rest of the building. The measured n_{50} value is in the range between 4 – 12 1/h defined in the SIA-norm for unrenovated old buildings from before 1980s. The measured n_{50} value leads to a calculated air exchange rate ($n_{n_{50}}$) of 0.7 1/h. However, the adoption of such value in areas of natural ventilation leads to too high ventilation losses. Therefore, the adopted air exchange rate (n) in these areas of the building is set to 0.3 1/h, which is similar to the value proposed by Umwelt Bundesamt [27].

- Thermal transmittance:

The thermal transmittances of buildings components used in the thermal model are defined from measurements realised following the methodology described in **3.3.4 Building physics**, combined with available data concerning the building materials and data from literature.

Table 5.11: Thermal transmittance values adopted in the model (Building B)

	Roof	Glazed façade	Concrete façade	Block façade	Window
U [W/m²K]	0.65	0.55	0.29	0.90	3.00

The surface area of the different components is presented in **Table 5.12**.

The validated thermal transmittance values used in the model for each building component are presented in **Table 5.11**. It contains the thermal transmittance measured values for the roof, a façade with an outer glazed layer (here called glazed façade), a façade covered with concrete and small stones (here called concrete façade), a façade wall composed of concrete blocks (here called block façade), and the glass from the windows.

The thermal model developed in LESOSAI, following the EN 13790 monthly balance provides a Sankey diagram with the heat gains, calculated based on the internal and solar gains, and the need for heating to compensate the thermal losses, as presented in **Figure**

5.19. The thermal losses are calculated for the building components according to their characteristics.

Table 5.12: Surface areas of the different components (Building B)

	Roof	Glazed façade	Concrete façade	Block façade	Window
Surface area [m²]	5804	2436	658	1834	2610

The model is validated from the comparison between the heat gain, named as heating in **Figure 5.19**, with the specific consumption of the Central Building obtained from the distribution of the heat consumption data from the energy bill, with the different building blocks presented in **Table 5.10**.

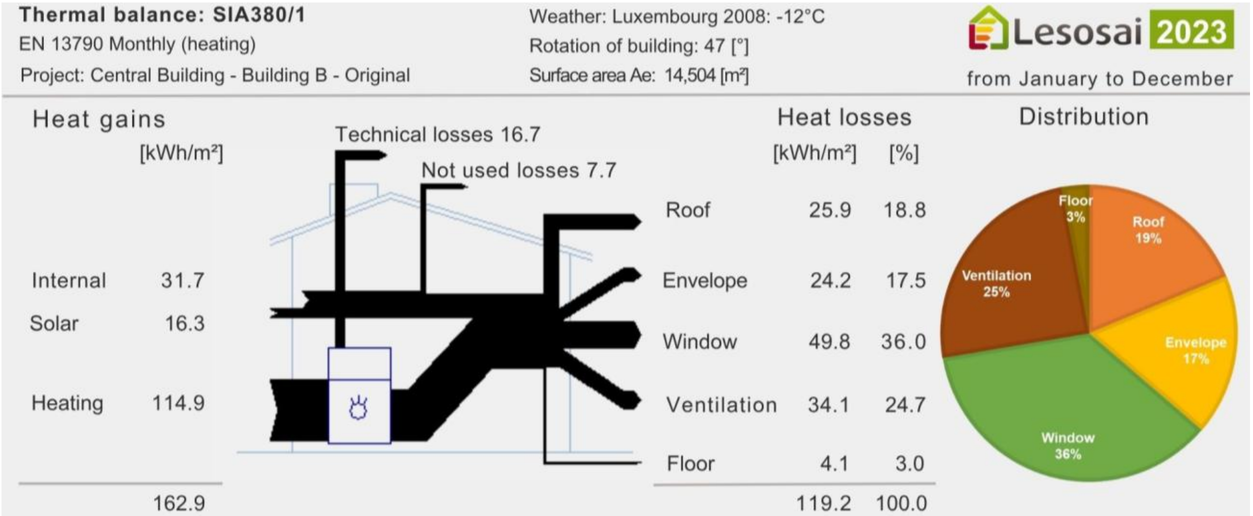


Figure 5.19: Thermal balance of the building (Building B)

The specific consumption shown in **Table 5.10** for Central Building for the reference year (2018) is 110 kWh/m^{2}a, while the output of the thermal model presented in **Figure 5.19** shows 115 kWh/m^{2}a, and 117 kWh/m^{2}a including hot water. The higher heating gains output of the thermal model including hot water, when compared the average consumptions measured from the energy bills distributed among the building blocks, can be explained by the uncertainties regarding the building characteristics, and limitations regarding the operational settings of the heating system. In the model, the heating needs are calculated based on the typical heating degree days of the building location, obtained from historical data, while the reduced operational modes observed in the real operations are not accounted for in the thermal model.

The distribution of thermal losses within the building, presented in **Figure 5.20**, allows to identify potential opportunities for energy savings.

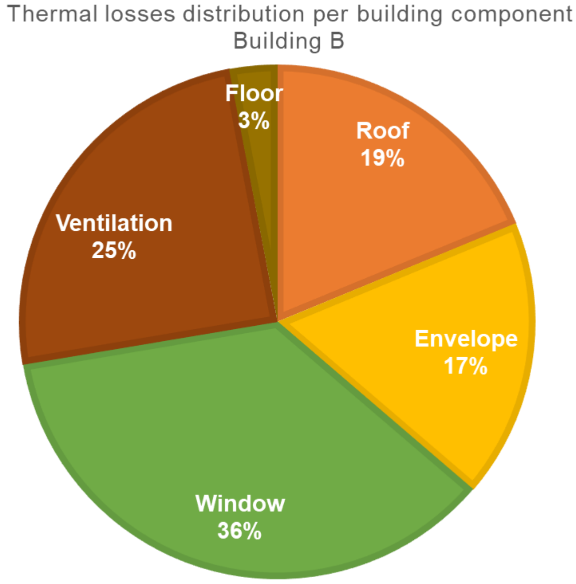


Figure 5.20: Thermal loss distribution per buildings component (Building B)

In the case of Building B the 72% of the thermal losses are happening through the windows (36%), the envelope (17%) and the roof (19%). Following the framework proposed in **Figure 5.1**, these represent potential energy-saving opportunities and must be further evaluated. The results from the energy audit provide the basis for identifying defining an intervention plan.

5.4. Energy audit outcomes

The stakeholders involved during the behavioural approach (Step 1) play a fundamental role in providing information on the physical properties of the building and usage patterns, as well as sharing information on actions already implemented, lessons learned, and challenges encountered in achieving impactful results. This information serves as a reference for the subsequent energy audit (Stage 2), thereby ensuring that the technical analysis is based on the reality of the building's use and management.

The energy audit, referring to Step 2 of the Framework, builds on this understanding by providing a detailed assessment of where and how energy is consumed within the studied educational buildings. The analysis of occupancy profiles shows demand concentrated during weekdays, particularly in the mornings and early afternoons, with opportunities for optimisation during evenings, weekends, and holidays when user comfort would not be compromised. Benchmark comparisons reveal that while thermal performance is bellow reference values, electricity consumption is consistently above, indicating a clear priority for electrical interventions in Step 3.

Detailed analysis of electricity consumption highlights three key areas for targeted measures. First, baseload consumption remains high, for periods when buildings are unoccupied, pointing to significant savings potential through improved scheduling and operational control of technical installations. Second, consumption distribution identifies priority systems for intervention. In Building B, outdated lighting and overuse of ventilation emerge as critical inefficiencies, while in Building C, high demand is linked to pumps for water treatment and heating, in the swimming pool. Third, thermal analysis of Building B reveals substantial heat losses through single-glazed aluminium windows, followed by the roof and envelope, offering opportunities for improving thermal efficiency, through pinpointed renovations.

By integrating the findings from Step 1 and Step 2, the framework establishes both the behavioural and technical priorities for intervention. The motivation and awareness of building users can support behavioural measures and operational adjustments, while technical audits provide the evidence base for targeting the most impactful systems. Together, they guide Step 3 towards interventions that are not only technically sound but also feasible within the organisational and behavioural context.

6. Energy- and carbon-saving interventions

This chapter corresponds to **Step 3** of the **Framework** presented in **Figure 3.1**, focusing on the development of energy- and carbon-saving interventions. These interventions are designed based on the potential energy savings identified through the comprehensive energy audits detailed in **Chapter 5** and are combined with strategies for integrating renewable energy sources into the operation of educational buildings. The objective is to address energy efficiency and sustainability by presenting a combined approach to reducing the carbon footprint of educational facilities.

Table 6.1: Summary of analysed energy- and carbon-saving interventions

Intervention	Description	Building
Reduced operational modes	Interventions to reduce energy consumption and operational costs, applied during empty periods and which do not require investments	
Swimming pool	Reviewing reduced operational modes for the pumps dedicated to water treatments and the mechanical ventilation during empty hours	Building C
Winter holidays	Reducing heating during winter holidays break	Building B
Closed sun blinds during night	Closing the sun blinds during the nights to reduce thermal losses	Building B
Sufficiency	Interventions to reduce energy consumption and operational costs, applied during working hours and which do not require investments	
Mechanical ventilation	Limiting the use of mechanical ventilation only when required	Building B
Lighting	Reducing lighting levels and operational hours in common areas	Building B
Swimming pool - winter holidays	Closing the swimming pool in between holidays during winter period	Building C
Renovation	Interventions to reduce energy consumption and operational costs, which do not interfere in the building operation, but requires investments	
Insulation	Improving the thermal resistance of radiator niches, window frames and the roof	Building B
Integration of renewable energy	Interventions to reduce carbon emissions, which do not interfere in the building operation, but requires investments and/or increases operational costs	
Photovoltaic panels	Adoption of photovoltaic systems to locally produce renewable electricity	Building C & D
HVO in heating boilers	Replacement of heating oil with hydrogenated vegetable oil in heating boilers to reduce the carbon emissions of heat production	Building D
Hydrogen in CHP engines	Replacement of natural gas with hydrogen in combined heat and power engines in district heating systems to reduce the carbon emissions	Building B & C

Reduced operational modes and sufficiency, are energy- and carbon-saving interventions that do not require financial or energetic investments, as presented in **Table 6.1**. These measures are primarily based on operational and behaviour changes. Their effectiveness can be directly assessed through the savings achieved during building operation. In contrast, the evaluation of renovation measures and the integration of renewable energy systems must account for the associated embodied energy and required financial investments. Renovation measures are considered advantageous when the energy and carbon savings they deliver exceed those that would result from demolishing the existing structure and constructing a new building. Finally, the integration of renewable energy plays a critical role in reducing carbon emissions in the building sector. This chapter is dedicated to evaluating their impact, as per the renovations, considering the related grey energy, as well as addressing the financial gap that still hinders their widespread adoption.

6.1. Reduced operational modes

The operational mode of technical equipment refers to the manner in which it is used, significantly influencing energy efficiency and, consequently, representing a key area for potential energy savings. The adoption of energy management systems that optimise performance by adapting operation to actual needs is becoming increasingly common. However, if poorly implemented, such systems may lead to higher energy consumption. Moreover, incompatibilities with older installations can further impede the intended improvements. This highlights the importance of understanding operational behaviour and maintaining continuous monitoring.

Adjusting operational modes to real needs in older buildings lead to important savings, in general with no or low investments. The proposed approach is based on the results from **5 Energy audit of educational buildings in Luxembourg**, combined with monitoring. Although the primary objective of any facility manager is to use energy only when necessary, it is common for equipment to operate unnecessarily due to mismanagement, which is often caused by inadequate monitoring.

A detailed understanding of building activities is essential to adapt operational settings to actual needs. It enables the definition of reduced operational modes during unoccupied periods such as night-time, weekends, and holidays. To implement appropriate adjustments, a thorough understanding of both user needs and technical systems is necessary, highlighting the importance of **Steps 1** and **2** of the **Framework**, the behavioural approach, and the energy audit. Most importantly, it requires ongoing monitoring of activities, to allow timely updates, and of consumption and operational settings, to verify and sustain the impact of the implemented measures.

6.1.1. Pumps and ventilation in a swimming pool during empty periods

Building C has an indoor swimming pool with 312.5 m^2, with an adjustable floor allowing to vary its depth and volume. In order to guarantee the water quality this pool is equipped with three pumps. The building also includes a mechanical ventilation system with a nominal air flow rate capacity of 22,000 m^3/h. These systems must operate continuously to ensure appropriate water and air quality, as well as to preserve the structural integrity of the building. During unoccupied periods, the systems operate in a reduced mode, as they cannot be completely shut down. Continuous water circulation and air ventilation are essential to maintain water quality, control humidity, and prevent the growth of harmful mould or bacteria in indoor swimming pool facilities. Nevertheless, there remains potential for further optimisation, as identified during the energy audit, and explored in this section.

Pumps dedicated to the water treatment

The swimming pool operates with three pumps running continuously. During periods of expected use (weekdays from 06:00 to 22:00 and Saturdays from 06:00 to 14:00) two pumps are active, while a single pump runs during off-hours (22:00 to 06:00 on weekdays and from 14:00 on Saturday until 06:00 on Monday). This schedule is pre-set according to the standard operating hours of the swimming pool, but does not always align with actual usage patterns. Measurements taken during the energy audit phase revealed that the system was operating on Sundays from 06:00 to 21:00, deviating from the programmed settings and highlighting a mismatch between intended and actual operation.

The local measurements displayed in **Figure 6.1**, indicate typical electrical power requirement of 17.3 kW for the pumps in normal operation, whereas only 11.5 kW is required for reduced operation. The data also show that on Sundays the pumping schedule is similar to weekdays, and during holiday weeks (Christmas holidays), although the school is closed, the pumping system follows the schedule of normal weeks. Consequently, the intervention strategy focuses in adjusting its operation to better align with actual needs, and to adopt reduced operational modes when the pool is not in use.

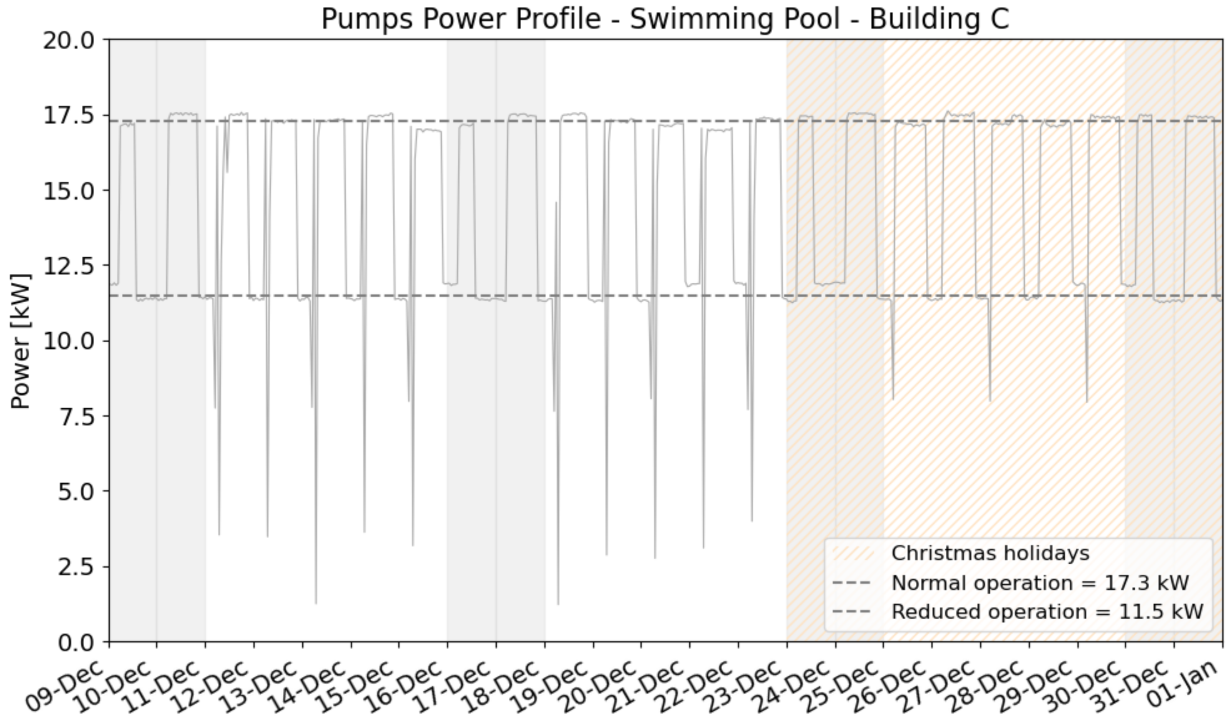


Figure 6.1: Power profile of the pumps used for water treatment of the swimming pool (Building C)

The analysis of the power requirement profile of the pumps indicates two approaches to reduce energy consumption of the pumps dedicated to the water treatment at this swimming pool. The first measure is to correct the pumping schedule, to ensure that it operates in reduced mode on Sundays, which leads to savings of 2.8 MWh/a. The second measure concerns holidays weeks during the school year.

The operation of the pumping system during the eight holiday weeks distributed throughout the year, represents an energy usage of 20.2 MWh/a. The shift to a reduced operational mode during this period, decreased consumption to 15.5 MWh/a, reaching an annual energy saving of approximately 4.7 MWh/a.

The simple correction of the deviation on Sunday schedule, and the adoption of reduced operation modes during the eight holiday weeks distributed over the school year represent together a 7.5 MWh/a reduction in the electricity consumption of the building, which represents almost 1% of the overall yearly consumption in 2018 (reference year). Further reductions could be achieved if the full operation of the system would only run while the swimming pool is in use, instead of following a schedule.

The carbon emission savings are calculated from the avoided electricity consumption, considering the environmental factor of the electricity mix of 0.367 $kgCO_2/kWh$, defined in the Luxemburgish directive concerning the energy efficiency of buildings [74]. This measure leads to a yearly reduction of 2,753 $kgCO_2/a$.

Mechanical ventilation

The electricity requirements of the mechanical ventilation system serving the swimming pool of Building C varies according to the needs. This variation occurs according to the airflow modulation defined based on a daily schedule and reference parameters. The daily schedule is established to reflect the occupancy, working on reduce mode, with an average power requirement of 3.6 kW, during weekdays between 22:00h and 07:00h, and from 20:00h to 07:00h over the weekend, calculated based on the local measurements. The airflow rate, and consequently the electricity consumption increases during daytime, with a minimum requirement of 6 kW, which increases to ensure the internal air temperature, and relative humidity levels at required levels, with peaks that can reach up to 17.5 kW, with an average of 7.4 kW. **Figure 6.2** shows the data obtained from local measurements between 30/10/2023 and 8/12/2023, marked in light brown, and the calculated average profile in dark grey. The “All Saints” holidays happened within this period, allowing to identify that the swimming pool technical installations operate following the same schedule even during empty periods.

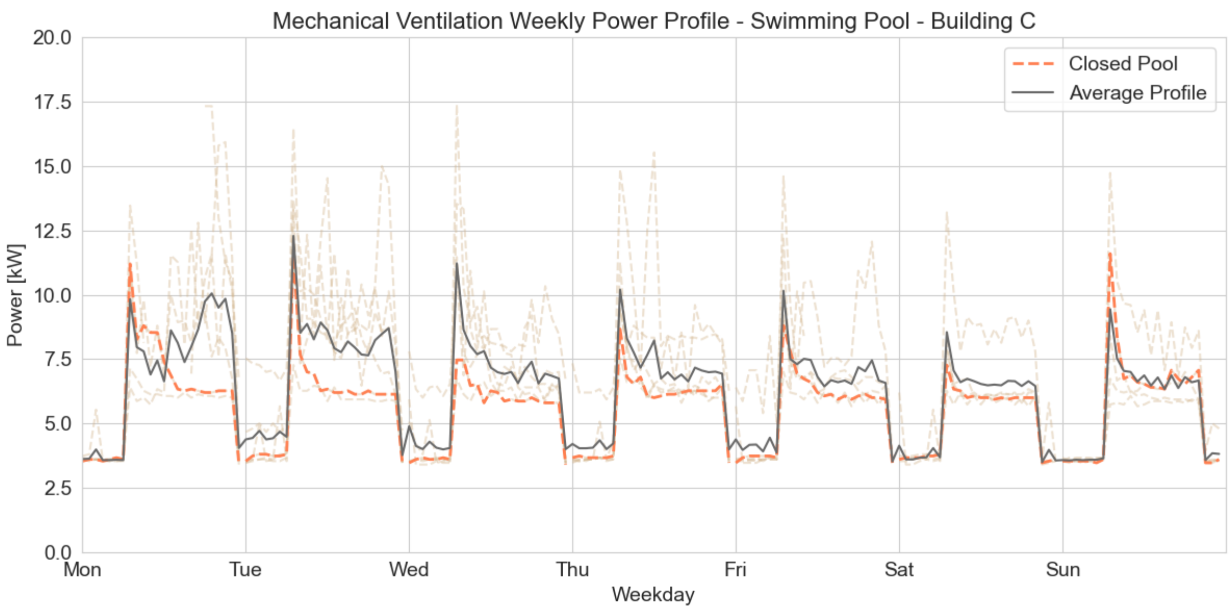


Figure 6.2: Power profile of the mechanical ventilation of the swimming pool (Building C)

Evaporation is significantly reduced during periods when the swimming pool is not in operation, as the air layer above the surface quickly reaches saturation when water movement is minimal. Under these conditions, the ventilation system can operate at its lowest setting, serving only to extract any potentially harmful by-products of water treatment and to prevent condensation that could compromise the structural integrity of the building. This reduction in ventilation also helps to limit heat losses. Consequently, adopting a reduced operational mode for the pumps during non-use periods enables a corresponding decrease in mechanical ventilation, thereby further optimising energy savings.

The mechanical ventilation consumes 8.5 MWh/a during the eight holiday weeks where the school is closed. The adoption of a reduced operational mode during this period, considering that the space is not used, only requires 5.6 MWh/a, leading to savings of 2.9 MWh/a. Adapting the operations to the same weekend schedule of the pumps lead to further savings of 1.1 MWh/a. Therefore, the adoption of reduced operational modes matching the real use of the swimming pool leads to overall savings of 4 MWh/a, which represents 0.4% of the overall consumption of Building C, in the reference year (2018).

The carbon emission savings is calculated based on the avoided electricity consumption, taking into consideration the so-called environmental factor of the electricity mix presented in **Table 3.9**. Therefore, the total carbon savings from this measure are quantified as 1,468 $kgCO_2$/a.

6.1.2. Radiators

The heating system of Building B is centrally controlled and is configured to ensure 20°C during operational days (Mondays to Saturdays from 05:00h to 18:00h), and 15°C over night, reducing to anti-freeze on Sunday afternoon, during the heating season, as presented in **Figure 6.3**. This measure reduces the energy consumption during unoccupied periods, and heat losses, by reducing the temperature difference between inside and outside, without impacting comfort of users.

The analysis of the data from **Figure 6.3** also shows that at 05:00h, once the heating system is set to normal operation, it reaches 20°C in less than 2h, even on colder early Mondays, when the lower inside temperatures are observed. It also proves potential to increase energy savings by starting to heat only at 06:00h, reducing the nighttime temperatures to the same level as Sunday afternoon, and starting the weekend set on Saturday afternoon, considering the very low occupancy during this period.

The radiators in Building B are controlled by thermostatics valves. In November 2022, fixed valves were installed in most radiators. They are set to 16°C in the hallways and 20°C at the classrooms and offices. This measure aims to improve efficiency with the centralised control. Combined with the re-balancing of the system, it led to savings of thermal energy of almost 9% in 2023 in comparison to 2022. However, the adoption of fixed thermostatic valves also incurred in comfort plaints. The building is characterised by important thermal losses, and at certain parts of the building, the 20°C could not be reached.

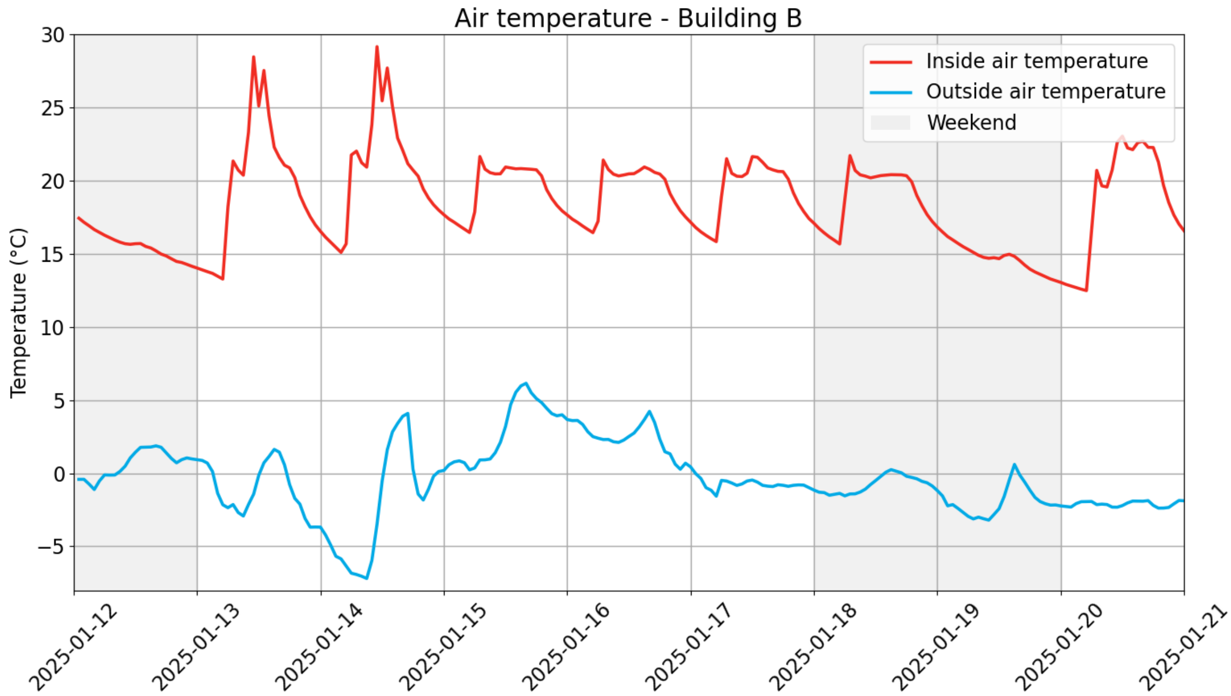


Figure 6.3: Air temperature inside and outside the building (Building B)

The use of adjustable valves requires informing users, training staff and a close management, but it may also allow to improve comfort and energy savings. If well used, these valves allow users to adjust to their comfort requirements while in the room, and to reduce completely once they leave. In educational buildings it is common to have periods with more intense activities, and other with lower occupancy, due to the programme. The same applies to offices, with the growing trend of home-office. The adjustable valves, allow to reduce to the minimum operational mode, once spaces are not in use, and to heat them up, once required.

A combined action between the central heating management, instructions to the buildings users to reduce the thermostat once they leave, the cleaning staff, which clear the rooms every afternoon, and the security team, responsible for opening the booked rooms in the morning, could lead to important energy savings, without impacting comfort.

Reduced heating during winter holidays

A campaign to reduce energy consumption during winter holidays was initiated in December/2024 at Building B. Collaborators were asked to adopt measures to reduce their consumption to the minimum necessary. Furthermore, between the 21/12/2024 and 30/12/2024, the central heating system was reduced by 5°C, changing the reference set point to 15°C for radiators with thermostatic valves in position 3. This measure considered that the building would be empty during this period due to the winter holidays and the end of the year festivities.

The energy savings related to 9 days reduced operation of the heating system is simulated based on the thermal model presented in **5.3 Thermal analysis**. It represents a decrease of 24 MWh or 32% in the heat requirement during the reduced operational mode period, 9% of the required heating gains in December, and 2% reduction on the annual heat energy demand, obtained from the thermal model.

Table 6.2: Monthly heating degree days in Luxembourg [106]

Monthly Heating Degree Days [Kd]												
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2022	559	430	398	318	70	6	0	0	154	203	380	537
2023	515	444	426	346	147	0	6	55	48	226	421	481
2024	577	392	376	297	165	93	25	5	128	261	438	544
Average	***550***	***422***	***400***	***320***	***127***	***33***	***10***	***20***	***110***	***230***	***413***	***521***

To evaluate the thermal energy savings associated with this measure, the analysis was based on the actual consumption during the studied period. However, as discussed in **3.3.1 Energy data treatment**, heating demand is strongly influenced by meteorological conditions. This means that a direct comparison of raw consumption data across different years may not provide a reliable basis for assessing energy performance. Therefore, monthly heating degree days (HDD) from 2022 to 2024 were analysed. This analysis showed that the HDD values for December 2022 and December 2024 differ by only 1%, indicating similar heating needs during both periods (**Table 6.2**). As presented in **Table 6.2**, the thermal energy consumption in December 2024 was 27 MWh lower than in

December 2022. Given the comparable external conditions, this reduction can be reasonably attributed to the energy-saving measures implemented in the building.

Table 6.3: Monthly heating energy consumption of Central Building - Building B

Monthly Heating Energy Consumption [MWh/month]												
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2022	249	199	169	123	28	2	0	0	54	86	141	227
2023	169	233	174	133	58	1	0	0	5	73	152	195
2024	241	176	146	106	50	23	2	1	25	85	154	200

Further analysis relies on the normalisation of the consumption considering the average of values from **Table 6.2**. This approach has shown a reduction ranging from 9% to 13% observed in December 2024 when compared to the same month in the preceding years, 2023 and 2022, respectively. It represents savings of 2% in the yearly heat energy consumption of the building, considering the data from Central Building, in 2018.

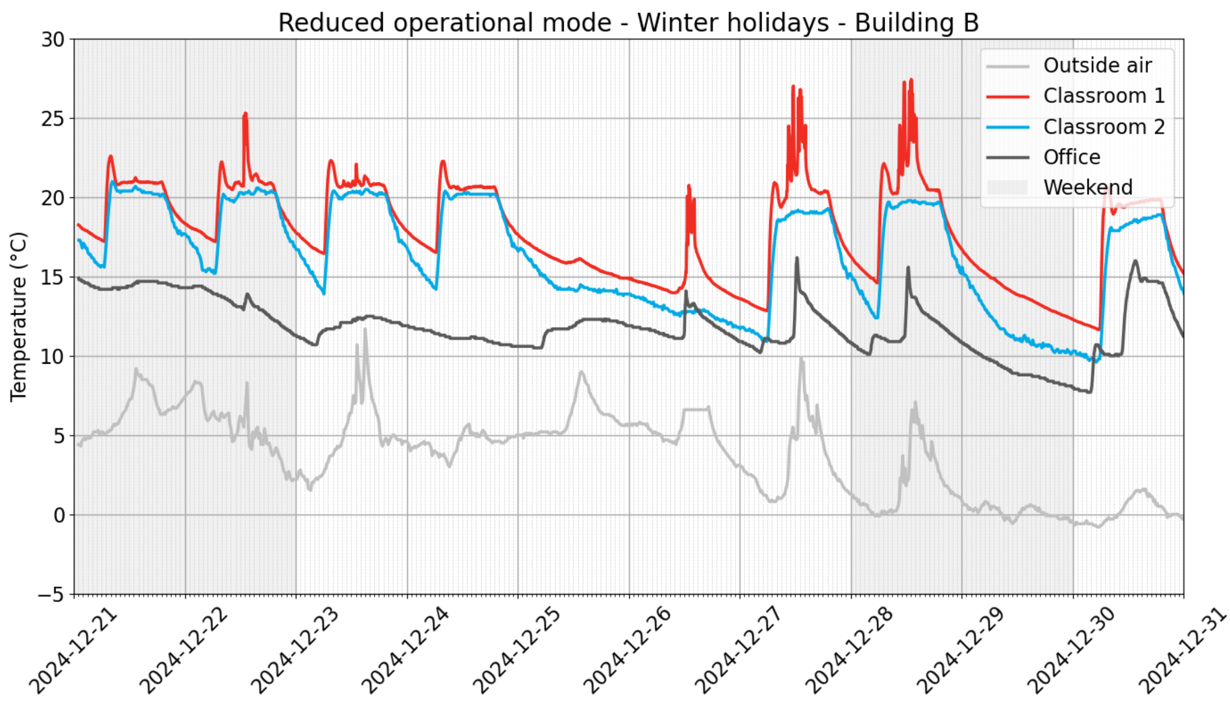


Figure 6.4: Air temperature profile during winter holidays at one office (reduced operational mode), two classroom (normal operation), and outside (Building B)

The findings of the present study demonstrate that the simulated and measured heating energy savings show similar results, thus validating the implemented measure. However, the monitoring data from two classrooms and one office during the reduced operational mode, displayed in **Figure 6.4**, period indicates that the measure was not fully applied in a section of the building where the classrooms are located. This highlights the potential for further savings in the future, related to the adoption of lower temperatures and a thorough implementation.

The peaks in inside air temperature observed in **Figure 6.4** correspond to occasions when direct solar irradiance affected the temperature sensor. This exposure causes localised heating of the sensor, leading to brief overestimations of the actual indoor air temperature due to the sensitivity to radiant energy rather than ambient air conditions alone.

The analysis presented in **Figure 6.4** indicates that additional energy savings can be achieved by reducing the minimum indoor temperature to 10 °C, rather than 15 °C, in accordance with the Office profile. Implementing this adjustment results in simulated savings of 41 MWh, representing an improvement of approximately 40% compared with the measure currently in place. Given that the building is unoccupied during this period, maintaining the additional 5 °C is unnecessary and leads to avoidable energy consumption.

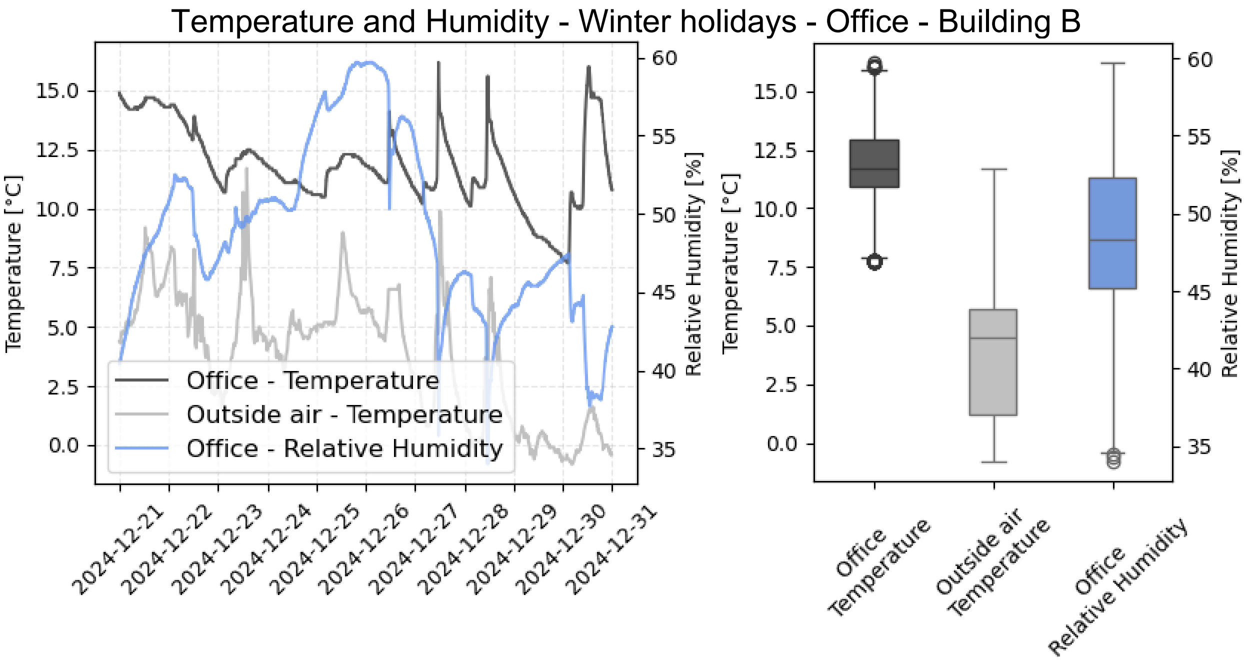


Figure 6.5: Distribution of air temperature and relative humidity inside the office, and outside air temperature between 21/12/2024 and 30/12/2024 (Building B)

Figure 6.5 focus on the data from the Office, where the internal temperatures were further reduced. The plot shows that during the nine-day winter holiday period the average outside air temperature was 4.5°C. It also shows that the average indoor temperature was 11.7°C, with an average relative humidity of 48%, due to the low occupancy and the absence of significant internal moisture sources. Under these conditions, the dew point of the indoor air is approximately 1°C. As condensation can only occur on surfaces below this temperature, and no building surfaces are expected to fall below 5°C, condensation risk is negligible.

Even when considering the maximum measured relative humidity of 60% at the lowest temperature in the office of 12.5°C, the dew point of the indoor air is approximately 5°C, and this condition was only observed for one day (10% of the reduced-mode period). Furthermore, once the heating system was re-established, the temperature inside the Office was re-stored within half a day.

The implementation phase requires verification, as highlighted in **Figure 6.4**. The air temperature profile in the two classrooms, located at the same block of the Central Building, of Building B, shows that during the winter holidays, the heating system operated under normal mode, with a set up temperature of 20°C during the day. A decrease is observed between the 25th and 27th of December, following the Sunday schedule, and it subsequently reverts to the standard schedule from the 28th of December onwards.

The carbon savings from such measure refers to the avoided heat consumption. It is calculated for both, the measured reduction of 27 MWh in December 2024, and the potential savings of 41 MWh, from a thorough implementation. The heat consumed in Building B is produced by a combined heat and power system, operating with 50% natural gas and 50% renewable fuels, and the carbon emission savings is calculated following the methodology presented in **3.5.2 Impact of interventions on carbon emissions**. The avoided carbon emissions in the year of 2024, is calculated as 3,483 $kgCO_2$, while a potential to save 5,289 $kgCO_2$ is identified for the same measure, requiring only monitoring and verification to ensure adequate implementation.

6.1.3. Window blinds

The Central Building of Building B has single glazed windows, most of them with external sun blinds. To reduce the heat losses during the night, it is proposed to close the external blinds to reduce their thermal transmittance, by adding an extra air layer to the window.

The improvement of the thermal transmittance of the window glass is evaluated through two calculations, considering the properties of the materials, and measuring the thermal transmittance, using the heat flow meter, as described in **3.3.4 Building physics**.

The calculation considers a glass with 4 mm and thermal conductivity of 0.81 W/mK, and a polyvinyl chloride (PVC) external blind, with 1 cm and thermal conductivity of 0.2 W/mK. The internal and external thermal surface resistances, as well as the resistance of the air layer is calculated based on the EN ISO 9646:1996, leading to a calculated thermal transmittance of 5.71 W/m^{2}K for the window glass with opened blinds. The scenario with closed windows blinds is calculated considering a 5 cm air gap between 40% of the window and the external blind, and 10 cm for the remaining surface. The adopted values are 0.13 m^{2}K/W, 0.04 m^{2}K/W, 0.21 m^{2}K/W, and 0.22 m^{2}K/W, respectively. These values lead to a calculated thermal transmittance of 2.27 W/m^{2}K. It must be highlighted that the resistance of the glass contributes to only 1%, while the air layer represents 48%.

The thermal transmittance of the glass of two windows was measured simultaneously, under the same internal and external air temperature conditions. One window with open blinds, and the other one with closed blinds. The measurements led to a thermal transmittance of 2.38 W/m^{2}K for the window glass with opened blinds, and 1.30 W/m^{2}K for the window glass with the closed blind. There is as difference of 60% and 45% between the calculated and the measured thermal transmittance values, for the scenarios of opened and closed blinds. This is meanly due to the resistance of the glass, 94% higher in the measurements, in comparison with the calculated value. Furthermore, the measured internal and external surface resistances are also up to 75% higher than the values recommended in the norm. This is explained by the conservative approach of the norm, but it also highlights that the measurements only reflect the conditions during the period when they were taken.

Aiming to reduce the impact of the internal and external surface resistances an average between the measured and the norm values are adopted to represent the variations over the year. This leads to thermal transmittances of 3.03 W/m^{2}K for the window glass with opened blinds, and 1.39 W/m^{2}K for the window glass with the closed blind.

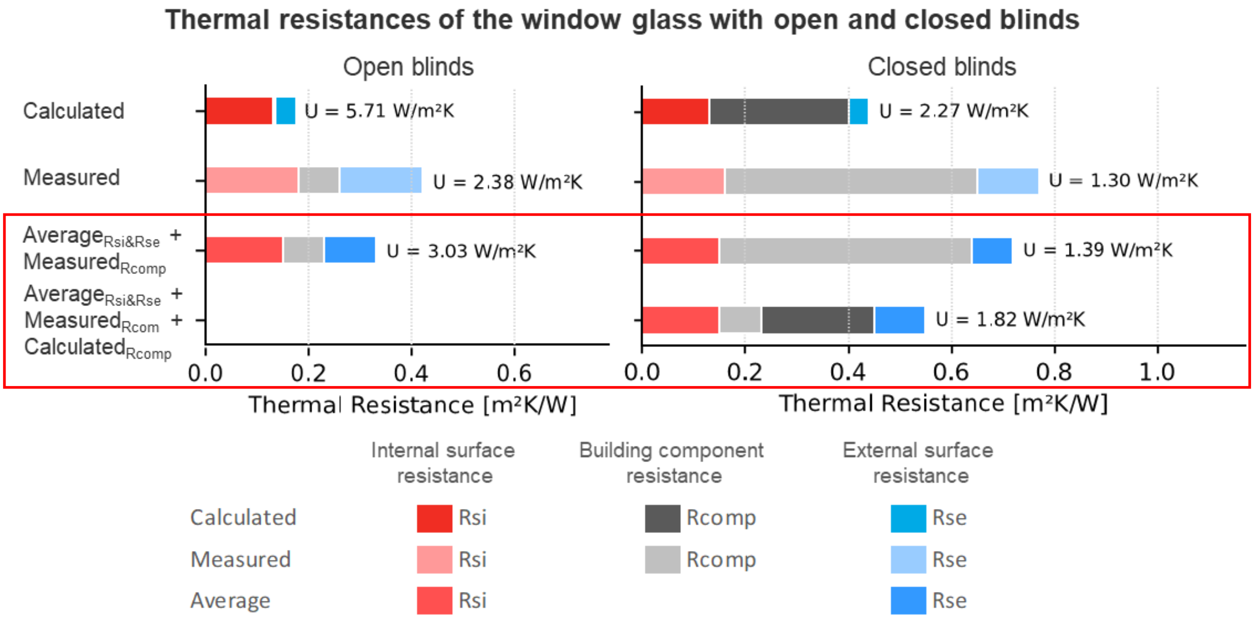


Figure 6.6: Thermal resistances of the window glass (Building B)

The impact of the closed blinds is also assessed from the addition of the 0.21 m^2K /W added resistance from the air layer proposed by the norm, plus the measured conditions of the window glass with the opened blind. This approach led to a thermal transmittance of 1.82 W/m^2K, which is 40% higher than the measured value, but in 20% lower than the originally calculated value. The findings demonstrate the impact of real-world conditions on thermal resistances, and the reduction on thermal losses through the window, as shown in **Figure 6.6**.

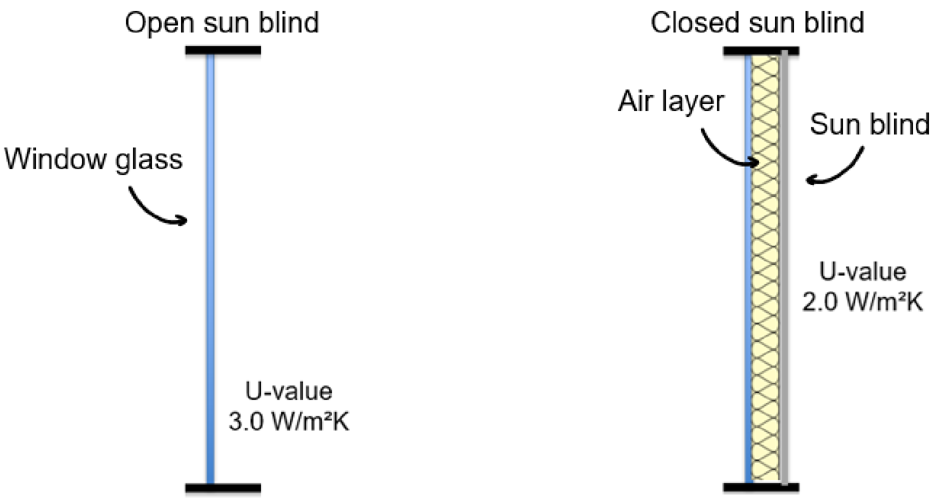


Figure 6.7: Schematic representation of the extra thermal resistance offered by the air layer between the glass and the sun blind (Building B)

Inside and outside air temperature distribution (Oct/2024 - Mar/2025)

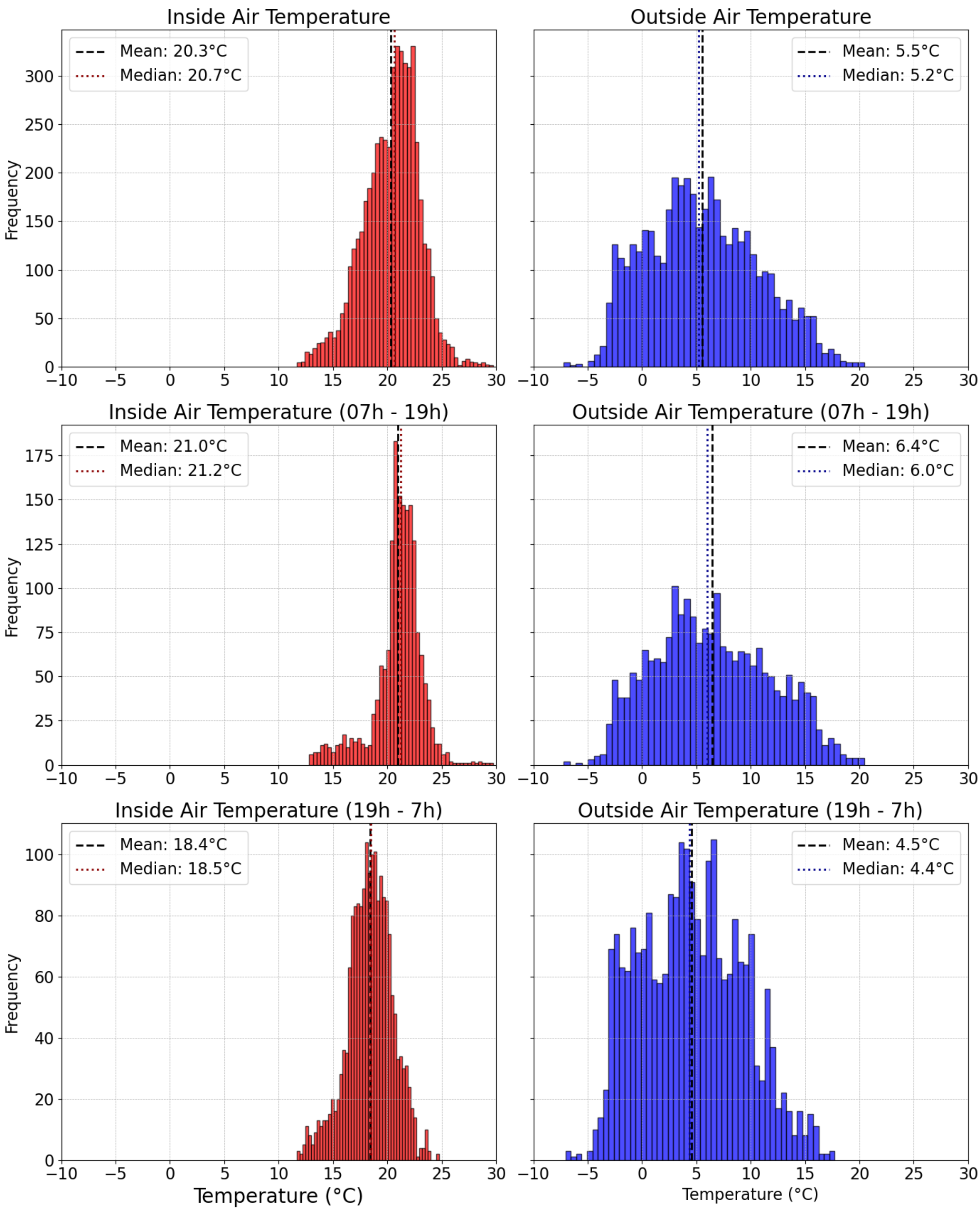


Figure 6.8: Inside and outside air temperature distribution between Oct/2024 and Mar/2025, for the full period, only during the day (7h - 19h), and only during nighttime (19h - 7h) (Building B)

Further energy savings are calculated considering thermal transmittance values of 3.00 W/m^{2}K for the window glass with opened blinds, and 1.60 W/m^{2}K for the window glass with the closed blind, as an average between the two last scenarios. The final thermal transmittances of the windows are 3.00 W/m^{2}K and 2.00 W/m^{2}K, for open and closed blinds, respectively. These values are obtained considering that the window frame has a thermal transmittance of 3.00 W/m^{2}K, and represent 30% of the surface area of the window, as shown in **Figure 6.7**.

The temperature difference between inside and outside is higher during night-time. According to meteorological data from Agrimeteo in Luxembourg, from Oct/2024 until Mar/2025, outside temperatures are in average, 1.9°C lower during the night (19h to 7h), than during the day, and it represents 70% of the average temperature between 7h and 19h, as shown in **Figure 6.8** [114]. However, the variation is also registered inside the building, due to the adoption of reduce operational modes when the building is empty. The analysis temperature difference between inside and outside air, from Oct/2024 until Mar/2025, shows an average of 13.9°C for the full period, and 13.7°C for the period between 19h to 7h. Therefore, the energy-saving analysis will be carried out considering the full period.

In the Central Building of Building B, from the total of 507 windows, 132 windows do not have blinds. From this, 100 windows are placed in hallways, where radiators operate with lower temperature setpoints. Therefore, the analysis is separated into two scenarios. Scenario 1 with 407 windows in the classrooms and offices, and Scenario 2 including the 100 windows from in the common areas.

The energy-savings related to the extra air layer added to the window by closing the blinds overnight is analysed based on the thermal model established the Central Building of Building B. As outlined in **5.3 Thermal analysis**, a significant proportion of the thermal losses, amounting to 41%, occur through the windows. Of these losses, 77%, concerns the 407 windows that are equipped with blinds or have the potential for retrofitting them. The thermal losses of these windows, with opened blinds, account for 551 MWh/a. Conversely, when the blinds are closed for a period of 12 hours, the thermal losses are simulated as 197 MWh/a. Therefore, considering the blinds closed for half of the period leads to losses of 472 MWh/a, representing a reduction of 78 MWh/a, as presented in Scenario 1 of **Table 6.4**, or 5% of the overall thermal energy consumption of the Central Building in 2018 (reference year). Scenario 2 from **Table 6.4** show further savings of 14 MWh/a, with a total of 92 MWh/a, with the addition of sun blinds in the 100 windows placed at the hallways.

Table 6.4: Total and specific yearly reduction in heat consumption per scenario for current stage and all windows with operational sun blinds

Heat consumption reduction	Scenario 1 *407 windows*		Scenario 2 *507 windows*	
Current status	63 MWh/a	2.7 kWh/m^{2}a	63 MWh/a	2.7 kWh/m^{2}a
All windows	78 MWh/a	3.3 kWh/m^{2}a	92 MWh/a	3.9 kWh/m^{2}a

This measure does not require any direct energetic or financial investments, however from the 407 windows, 8% do not have sun blinds, and 12% are broken. The disposal of 50 broken blinds and addition of 82 new ones increases the primary embodied energy of the building by 73 MWh, with carbon equivalent emissions of 17 tCO_2. This is calculated based on the information presented in **Table 6.5** obtained from the environmental product declaration (EPD) of sun blinds, from the Ökobaudat data base [107]. The operational energy savings related to the addition of the 82 new sun blinds represents 15 MWh/a in terms of final energy.

The compensation time for the added primary embodied energy and carbon equivalent emissions are calculated based on the methodology presented in **3.5.1 Energetic impact of interventions** and **3.5.2 Impact of interventions on carbon emissions**, considering the avoided heat consumption in Building B. The heat is provided by a district heating network, connected to combined heat and power systems, with half of the production coming from fossil fuels. The adoption of the weighted factor from

Table 3.8 and **Table 3.9** leads to energetic and carbon emissions compensation times between 8 years and 9 years, for both Scenarios 1 and 2.

Table 6.5: Primary embodied energy added due to the disposal and installation of one window blind (3.2 m^2), concerning the disposal stage (C3-C4) and product-stage (A1-A3)

Material	Quantity per window	PENRT	Primary embodied energy	Climate change	Carbon equivalent emissions
Treatment and disposal of existing blinds	3.2 m^2	5.6 MJ/m^2 (C3-C4)	4.9 kWh	11.2 $kgCO_2/m^2$ (C3-C4)	35.8 $kgCO_2$
Sun blinds	3.2 m^2	994 MJ/m^2 (A1-A3)	883.6 kWh	59 $kgCO_2/m^2$ (A1-A3)	188.8 $kgCO_2$

The replacement of broken window blinds and addition of a motorised systems is analysed according to the methodology in **3.5.3 Economic impact of interventions**, and presented in **Table 6.6**. The cost amounts to 1,353 €/window, with 56% attributed to standard maintenance and 44% allocated to measures that promote user engagement, since the integration of electric motors simplifies the operation of the blinds, thereby increasing the likelihood of consistent use.

The economic analysis of the investments corresponding to Scenario 1 (407 windows) is presented in **Table 6.6**. The focus is in 32 windows which need installation of new window blinds, and further 50 windows which needs replacement, as part of normal maintenance. Finally, with regards to the installation of electric motors, 22 windows are already equipped with such device.

Table 6.6: Investment in repairing the window blinds and converting into electric blinds

Measures	Quantity [units]	Unit cost [€/window]	Total Investment [€]
Installing new window blinds			**59,556**
Removal and disposal	50	71	3,550
Installing new sun blinds	82	683	56,006
Installing electric motor			**228,445**
Motor	380	434	164,920
Electric installation	385	165	63,525
Total			**293,001**

The total required investment for Scenario 1 is presented in **Table 6.6**, which increases by 128,200 € in Scenario 2 (507 windows), for installing new sun blinds and electric motor. The implementation of such measure does not imperatively depend on financial investments. The investment of 59,556 € is mainly related to normal maintenance, but 37% refers to the addition of external blinds to windows which currently do not possess them. The payback time of installing 132 new window sun blinds in Scenario 2, considering only the non-maintenance costs to add, is calculated as 27 years, based on the yearly savings of 3,300 €/a in the energy bills.

The additional 228,445 € investment listed in **Table 6.6** is intended primarily to facilitate the opening and closing of the sun blinds, thereby improving user convenience and increasing the likelihood of implementation.

6.2. Sufficiency

Sufficiency refers to the concept of reducing energy consumption by focusing on using only what is necessary to meet essential needs, rather than relying solely on efficiency measures or technological upgrades. This comprises technical and behavioural aspects of energy uses, which are presented and discussed for each measure implemented in the studied buildings.

Over the years, energy efficiency measures have successfully reduced the consumption of technical installations in buildings. However, the energy savings achieved have often been offset by a parallel shift in consumption patterns (what is saved through improved efficiency is increasingly redirected toward meeting rising expectations for indoor thermal comfort). This growing demand for better-controlled indoor environments and extended comfort zones has contributed to a steady or even increasing overall energy use in buildings.

This situation underscores the limitations of efficiency-oriented strategies when considered isolated. As efficiency improvements are frequently offset by increased demand for indoor thermal comfort, there is a growing recognition of the need to complement these measures with sufficiency-oriented approaches. Sufficiency focuses on defining and promoting acceptable levels of service and comfort that align with sustainability goals, rather than continuously expanding them. Integrating sufficiency into building design, operation, and policy frameworks is therefore essential to achieving long-term reductions in energy consumption and mitigating the rebound effects associated with efficiency gains.

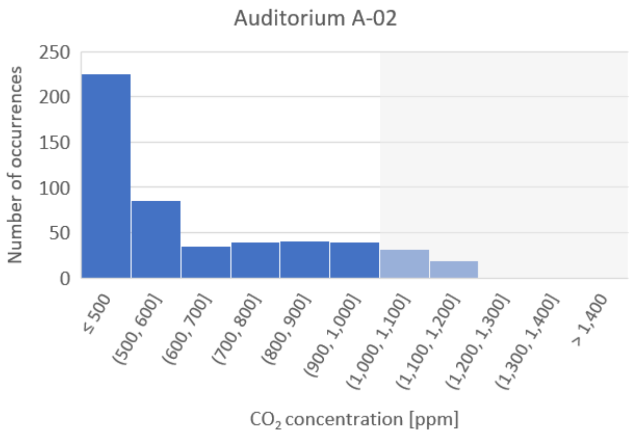
6.2.1. Mechanical ventilation in rooms with occupation above 50 people

The Central Building is equipped with mechanical ventilation to cover the requirements of specific parts of the building, which includes the kitchen, the canteen, a big conference room, and three auditoriums. However, as already discussed in previous chapters, and presented in **Figure 5.18**, Building B does not present a high level of air tightness.

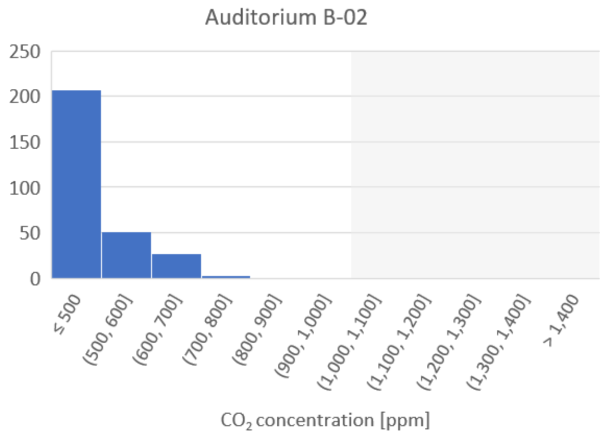
In the kitchen and canteen areas the mechanical ventilation is necessary to ensure the safe removal of moisture, and pollutants generated by cooking processes. These spaces typically produce high levels of grease, smoke, and odours, which can degrade air quality, requiring mechanical ventilation to improve both comfort and hygiene.

Auditoriums

In conference rooms with high occupancy, mechanical ventilation is used to maintain air quality and comfort. These spaces are often subject to rapid increases in carbon dioxide and humidity levels. Ventilation is necessary to provide a continuous supply of fresh air, regulate temperature, and prevent the buildup of indoor air pollutants, which can negatively affect concentration and overall well-being. However, Maas et al., (2019) showed in their study on the mechanical ventilation of one auditorium in Central Building that, due to the natural air infiltration combined with the opening of the windows, it had no significant impact on the perceived comfort of the users, while leading to a considerable electricity consumption [110]. Such results are confirmed by the monitoring of CO_2 concentrations in the three auditoriums, realized in 2024 and 2025, presented in **Figure 6.9**, showing that even without mechanical ventilation, the air quality in the auditoriums stayed within an acceptable range for more than 90% of the measured period.



(a)



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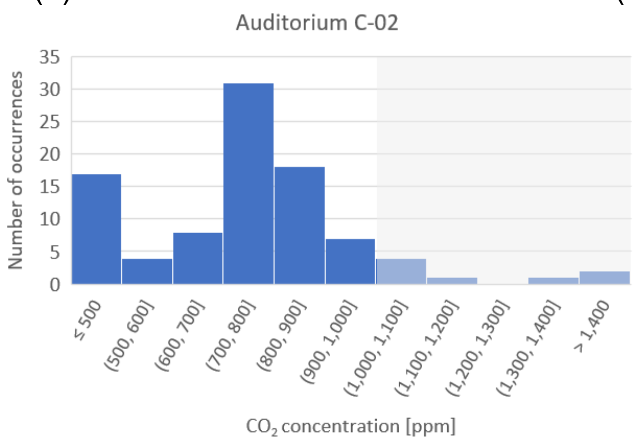

(c)

Figure 6.9: Histogram of carbon dioxide concentration in auditoriums without mechanical ventilation, with grey area marking concentrations above 1,000 ppm: (a) Auditorium A-02; (b) Auditorium B-02; (c) Auditorium C-02 (Building B)

The study from Maas et al. (2019) provides information regarding the power requirement of the mechanical ventilation (4.2 kW), and the number of daily operational hours (11h/d during the semester), measured for one auditorium at the central building [110]. From this data it is possible to calculate the yearly electrical consumption of 8 MWh/a in one auditorium. Considering that the three auditoriums have the similar characteristics, such as size, disposition, and utilisation pattern, it is possible to infer that their consumption count for 24 MWh/a, which represented 2% of the Central Building consumption in 2018 (reference year). The carbon emission savings are quantified as 8,808 kgCO_2/a, following the methodology presented in **3.5.2 Impact of interventions on carbon emissions**.

The low air tightness of the auditoriums, combined with the frequent opening of the window, when fresh air is needed, and the similar, generally good levels of perceived comfort independently of the mechanical ventilation, presented by Maas et al. (2019) showed that this electricity consumption is not justified, and led to the decision to permanently turn off the three systems in 2022 [110].

Conference Room

The conference room is primarily used for events throughout the year and serves as an examination space during the January and June exam periods. With a maximum occupancy of 150 people, mechanical ventilation is required when the room operates at full capacity, and the windows cannot be opened. However, based on the intermittent usage pattern and the findings of Maas et al., (2019), it was decided in 2022 to restrict the operation of the mechanical ventilation system to periods when it is strictly necessary [110].

Prior to this change, the mechanical ventilation system operated approximately twelve hours per day, from Monday to Saturday, resulting in an annual energy consumption of 10 MWh/a. An analysis of the occupancy patterns of the conference room indicates that ventilation is actually required during only 10% of the original operating hours. Therefore, aligning system operation with actual usage could lead to energy savings of up to 9 MWh/a, representing 1% of the total energy consumption of the Central Building in 2018 (reference year).

The avoided electricity consumption leads to savings of carbon emissions. Following the methodology presented in **3.5.2 Impact of interventions on carbon emissions,** yearly savings of 3,303 kgCO_2/a are expected [74].

Despite the revised operational strategy, on-site measurements revealed that the ventilation system continued to run even when the room was unoccupied. This indicates that, although it represents a significant potential for energy saving, impactful results can only be achieved through an integrated operational management.

6.2.2. Lighting in common areas

Appropriate lighting system in buildings is essential for productivity and well-being. Natural daylight is generally preferred over artificial lighting due to its positive effects on comfort and energy savings. However, artificial lighting remains necessary, especially during periods of low daylight availability or in interior zones with limited access to natural light.

In buildings with long operational hours, such as educational facilities, lighting contributes significantly to overall electricity consumption, particularly in the case where outdated systems are still in use.

Upgrading to more energy-efficient lighting technologies and integrating intelligent control systems, such as occupancy sensors and daylight-responsive dimming, as demonstrated by Thewes (2011) offer opportunities for reducing energy use by more than 80%, when compared with older systems [72]. However, it also leads to important investment, considering the large number of existing lamps. The gradual replacement is natural, since the old systems are no longer commercialised, and are slowly phasing out.

As stated in **5.2.3 Consumption distribution**, the lighting system represents more than a third of the total electricity consumption at the Central Building of Building B. While the comparison shows higher measured illuminance levels than the reference values. Therefore, at the end of 2022, 46% of the lighting system covering the common areas were disconnected, to reduce the illuminance levels to reach the 100 lx, which represents the minimum recommended levels for this type of usage.

The total disconnected power corresponds to 9.1 kW, which operated for 14 h/day, during weekdays, and for 8 h/day on Saturdays. The energy-saving measure also included the reduction of the operational hours, letting users turn on the lights when necessary, instead of following a daily schedule. These measures led to savings of 31 MWh/a, which represents 3% of the total electricity consumption of the Central Building in 2018 (reference year). Such reduction in electricity consumption represents yearly carbon emission savings of 11,377 $kgCO_2/a$, according to the environmental factor for the national electricity mix defined in the Luxemburgish directive on building energy efficiency of buildings [74].

6.2.3. Pumps and ventilation in a swimming pool during holidays

The swimming pool in Building C operates for 10 months each year and is drained during the summer holidays, during which the circulation pumps and ventilation system are switched off. This measure yields annual electricity savings of approximately 20 MWh/a, equivalent to 2% of the total yearly electricity consumption of the school, in 2018. As shown in the consumption distribution in **Figure 5.16**, the pumps used to maintain water quality standards are among the largest energy consumers in the sports hall building. Therefore, measures such as closing the swimming pool from mid-December until mid-February, would yield to the same savings in the electricity consumption regarding the pumps and the ventilation system, plus a reduction in the thermal consumption. While users would only be affected for four weeks, since the remaining four weeks correspond to holiday periods, when the school is closed. Besides, in January, students only have two weeks of normal classes, since the other two are dedicated to term exams and eventual retakes.

The avoided electricity consumption corresponds to 20 MWh/a, calculated based on the electricity consumptions measured in the swimming pool, and presented in **6.1.1 Pumps and ventilation in a swimming pool during empty periods**. This electricity consumption represents 2% of the overall consumption of Building C in 2018, adopted as reference year. In terms of heat, Seidel (2025) measured a consumption of 16 MWh/week in the same swimming pool in winter [115]. Therefore, closing the swimming pool for two months between the winter and carnival holidays would lead to reductions of 128 MWh/a, representing 7% of the heat consumption of Building C of the reference year.

The avoided electricity and heat consumption from this measure leads to savings on carbon emissions. They are calculated following the methodology presented in **3.5.1 Energetic impact of interventions** and **3.5.2 Impact of interventions on carbon emissions**. The energy savings from the closure of the swimming pool for the period of two months during winter, profiting from the Christmas and carnival holiday periods, yields to yearly carbon savings of 7 tCO_2/a, and 17 tCO_2/a, for electricity and heat, respectively.

The implementation of such measure requires verifying the utilisation rate of the swimming pool during this period. High utilisation rates justify the energy consumption. However, in case of low utilisation rates due to the school breaks and exam periods, this measure could easily lead to expressive energy and carbon savings without impacting the users, quantified as 24 tCO_2/a.

6.3. Renovations

Renovations aimed at improving energy efficiency primarily target reductions in energy consumption and associated carbon emissions by minimizing thermal losses. Insulation plays a key role in reducing heat losses by increasing the thermal resistance of building components, thereby lowering the energy needed to maintain comfort and reducing associated greenhouse gas emissions. Yet, producing insulation materials requires energy, and some are highly energy intensive. Moreover, while thermal resistance increases with insulation thickness, the resulting thermal transmittance decreases nonlinearly. As a result, the first few centimetres of insulation have the largest impact on heat losses, with additional thickness yielding diminishing returns. Therefore, the analysis of such measures needs to consider the savings over the entire life cycle of the building, including the embodied energy and carbon equivalent.

6.3.1. Radiator niche insulation

Heat loss through building envelopes is fundamentally driven by the temperature difference between the interior and exterior environments. The rate of heat transfer through structural elements increases with the increasing temperature difference. One particularly significant area of concern is the section of wall directly behind radiators (radiator niche). In these locations, the local temperature is considerably higher due to the proximity of the heat source, leading to higher heat losses.

The air temperature in the radiator niche of one classroom in Building B was measured in five different points from 01/10/2024 until 24/02/2025. The analysis of the temperature profile confirms that the central heating is operational between 05:00h and 18:00h from Mondays to Saturdays during the heating season, and it is off on Sundays, as presented in **Figure 6.10**, with the temperature profile from the second week of January/2025.

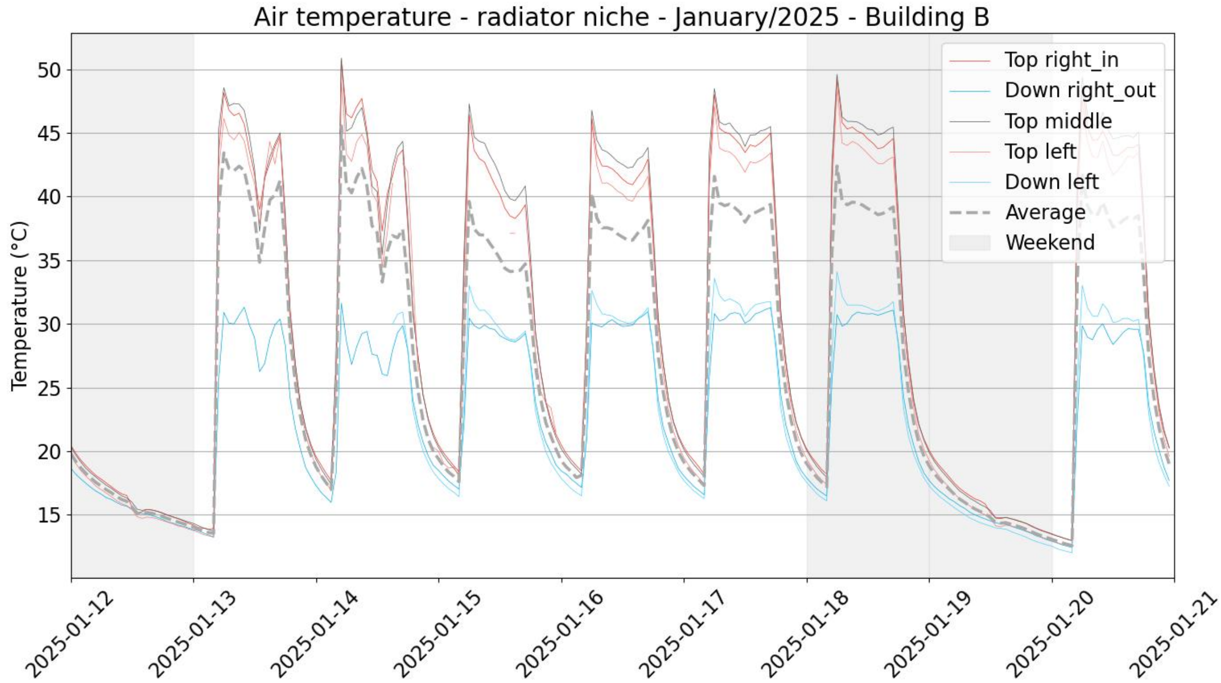

Figure 6.10: Air temperature in the radiator niche in January/2025 (Building B)

From **Figure 6.10**, it is observed that during the second week of January/2025 the top of the radiator niche reaches temperatures between 35°C and 50°C during the day, with the higher occurrences are registered in the morning. During this period the lower part of the radiator niche registers temperatures between 25°C and 35°C. Once the system is turned off, the upper and the lower parts of the niche present similar temperatures, with differences of 1.5°C.

The average air temperature observed in the radiator niche for the measured period, from 01/10/2024 until 24/02/2025, is of 24°C as observed in **Figure 6.11**, and 23.4°C is the extrapolated average value for the 210 days of the heating season, used in further analysis. The extrapolation of the measurements for the official heating season in Luxembourg, from October 1st to April 30th, is calculated based on the heating degree days from **Table 6.2**, where March and November present similar heating requirements, and April may be represented by the average between October and November.

The analysis of the average air temperature in the radiator niche during the heating season, following the same methodology as before, considering only the hours when the heating system was active, reveals an average temperature of 28.1°C. It considers that the system has operated for 2,184 hours, corresponding to 43% of the total heating season, based on the central heating schedule.

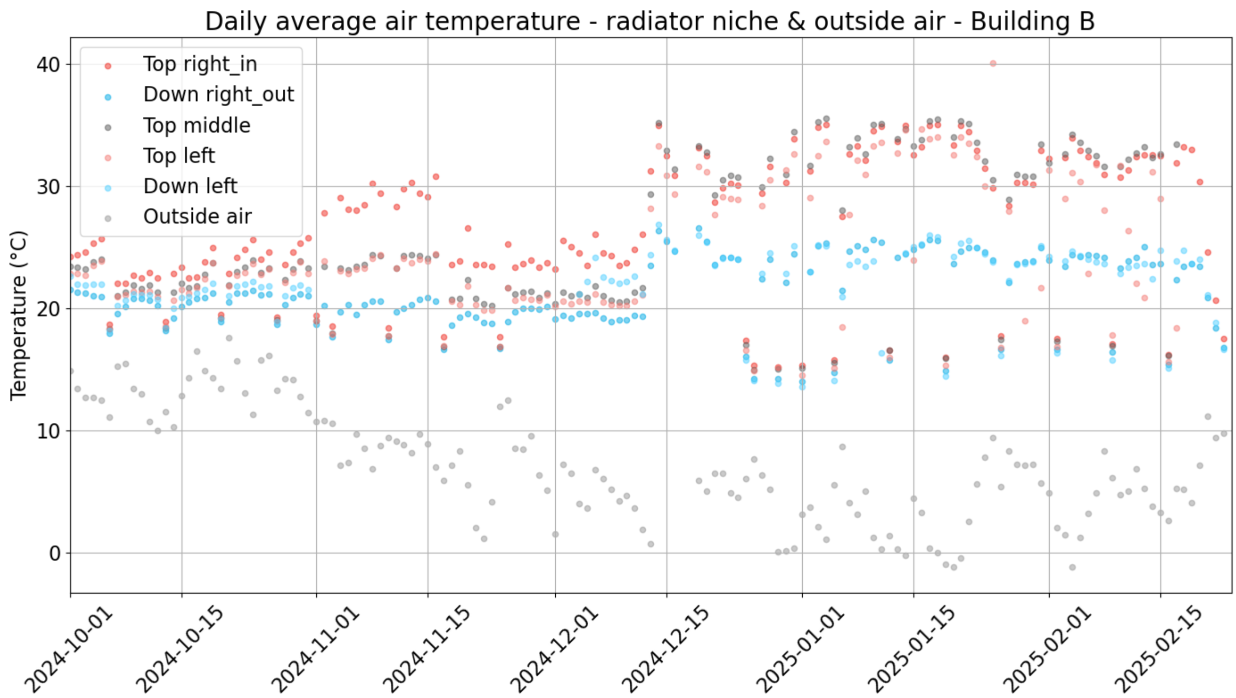

Figure 6.11: Daily average of the air temperature in the radiator niche and outside air from October/2024 to February/2025 (Building B)

The analysis of the entire measured period, presented in **Figure 6.11** shows that higher temperatures are registered between December and February. This pattern is confirmed by the heating degree days information from **Table 6.2**. The average measured outside air temperature between November and February represents 5.7°C, while the average of the operating hours of the heating system in this period corresponds to 6.9°C. The extrapolated outside average for the entire heating season represents 8.3°C, and is used in further analysis. The gradient temperature between the extrapolated average of inside and outside values is 15.2°C. This value is 8% higher than the average of heating degree days per day over the heating season in Luxembourg, between the years of 2017 and 2024, as presented in **Table 3.6**.

The analysis of the air temperature distribution in the radiator niche during working hours of January/2025 is presented in **Figure 6.12**. It shows the higher temperatures concentrated on the top part of the radiator with averages above 40°C. The lowest temperatures, in average 28.7°C are registered at the lower part of the niche. From the measured temperatures, the air temperature at the centre of the radiator niche is calculated as 35.3°C, when the average outside air temperature represents 4.3°C.

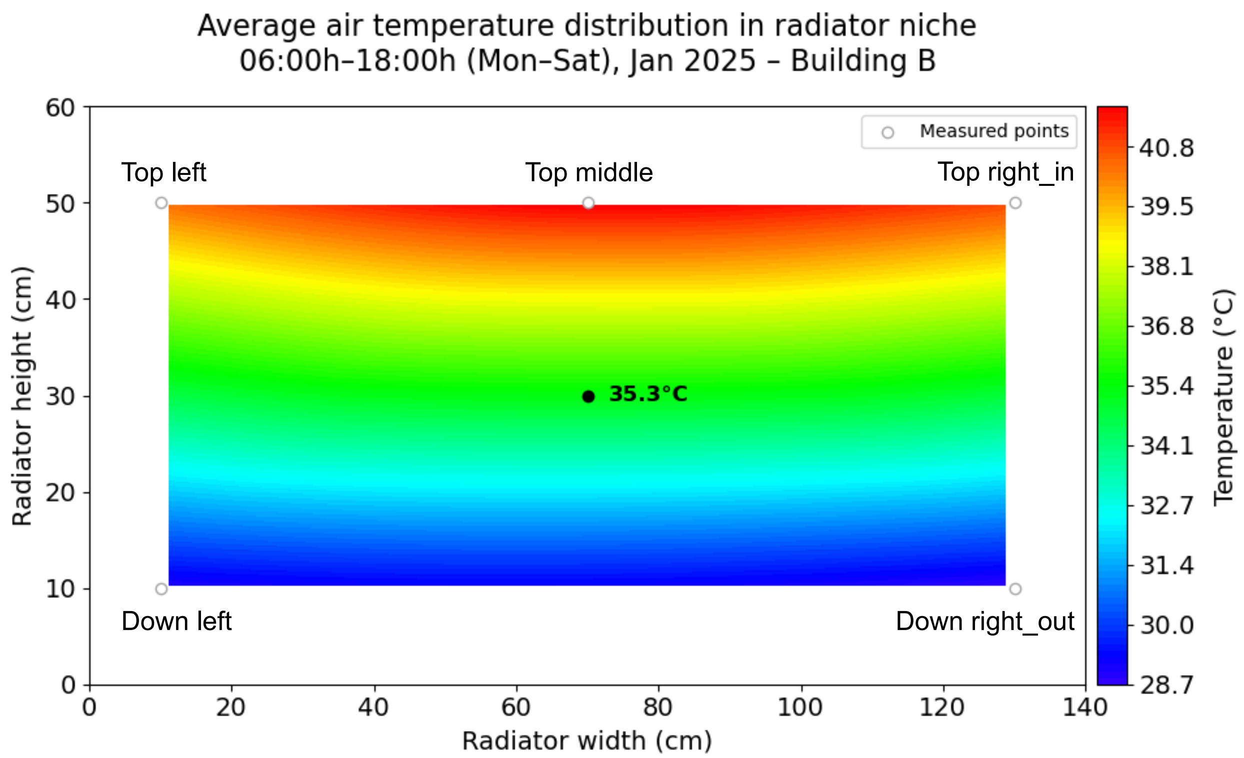

Figure 6.12: Average air temperature distribution in the radiator niche during working hours of January/2025 (Building B)

The risk of condensation was evaluated using the Glaser method, as defined in the EN ISO 13788:2012 standard [116]. The present analysis corroborates the findings of Latz et al. (2025), which demonstrate that the utilisation of thin layers of internal insulation is not problematic [117].

The measured thermal transmittance of the wall behind the radiator niche is presented in **Table 5.11**, under the name "glazed façade". This wall composed by cement brick, rockwool, an air layer and an external glazed panel, shows a thermal transmittance of 0.55 W/m^{2}K. To reduce thermal losses in this part of the façade, a 2 cm layer of insulation is added to the internal wall, as shown in **Figure 6.14** and outlined in **Figure 6.13**.

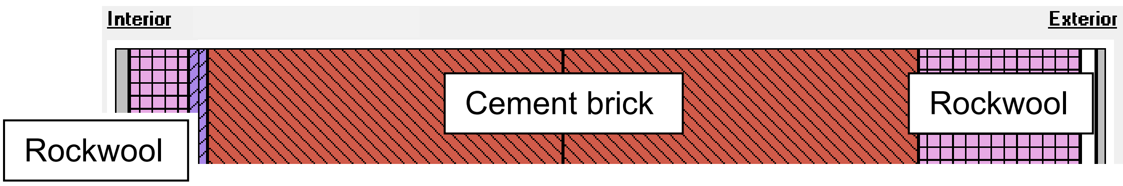

Figure 6.13: Addition of 2 cm of rockwool insulation in radiator niche (Building B)

The thermal transmittance of the niche after renovation is calculated, considering the thickness and the thermal conductivity of the added layers, reaching 0.38 W/m^{2}K, whereas the local measurement using the heat flow meter, following the methodology presented in **3.3.4 Building physics** shows 0.33 W/m^{2}K. The measured value is used in further analysis.

(a) (b) (c) (d) (e) (f)

Figure 6.14: Photos of the renovations. (a) View of the existing insulation and the glass on the external façade; (b) Internal view of the niche, without the radiators, before the renovation; (c) First layer of mortar and rockwool board; (d) Insulation being covered with plaster; (e) Net fitting for plaster finishing; (f) Final result (Building B)

The energy saving resulting from this pinpointed renovation is calculated from the difference between the heat losses happening at the radiator niche before and after the renovation, which is calculated using **Equation 6.1**.

Equation 6.1: Heat losses

$$E_{losses} = U \times (T_i - T_e) \times t \quad (6.1)$$

where:

E_{losses}	heat loses [kWh/m^2]
U	thermal transmittance of the building component [W/m^{2}K]
T_i	internal air temperature at the niche [°C]
T_e	external air temperature [°C]
t	period [h/a]

The heat losses are calculated for the official heating season, which extends from October 1st to April 30th (5040 h/a). **Table 6.7** shows the summary of the heat losses at the radiator niche before and after the renovation. They are quantified as 42.0 kWh/m^{2}a and 25.2 kWh/m^{2}a respectively. This results in an energy saving of 16.8 kWh/m^{2}a, with the surface referring to the area of the wall. The total surface area of all the radiator niches correspond to 915 m^2, representing a reduction of 15 MWh/a, or 1% of the overall yearly heat consumption of the Central Building of Building B, during the reference year (2018).

Table 6.7: Summary of heat losses before and after the renovation of the radiator niche

	Before renovation	**After renovation**	**Difference**
Thermal transmittance [W/m^{2}K]	0.55	0.33	0.22
Internal air temperature at the niche [°C]	23.4	23.4	-
External air temperature [°C]	8.3	8.3	-
Period [h/a]	5040	5040	-
Heat loses [kWh/m^{2}a]	42.0	25.2	16.8

The embodied energy added to the building due to the insulation of the radiator niche, as well as the related carbon equivalent emissions are calculated based on the environmental product declaration (EPD) of the used materials, from Ökobaudat database [107].

Table 6.8 shows the primary embodied energy content and the carbon equivalent emissions for the insulation of one radiator niche. From **Table 6.8** it is observed that 27% of the primary grey energy is related to the insulation, which is also responsible for 33% of the carbon emissions. The insulation of all radiator niches in Central Building leads to an added total primary embodied energy of 136 MWh and carbon equivalent emissions of 41 tCO_2.

Table 6.8: Primary embodied energy content and carbon equivalent emissions added to one radiator niche (1.5 m^2), concerning the product-stage (A1-A3)

Material	Quantity per niche (1.5 m^2)	PENRT (A1-A3)	Primary embodied energy	Climate change (A1-A3)	Carbon equivalent emissions
Adhesive mortar	1 kg	89.6 MJ/kg	24.9 kWh	5.0 $kgCO_2/kg$	5.0 $kgCO_2$
Rockwool	0.03 m^3	2,115 MJ/m^3	17.6 kWh	186.1 $kgCO_2/m^3$	5.6 $kgCO_2$
Mesh	1.5 m^2	10.3 MJ/ m^2	4.3 kWh	0.5 $kgCO_2/m^2$	0.7 $kgCO_2$
Reinforcing mortar	14 kg	4.5 MJ/kg	17.5 kWh	0.4 $kgCO_2/kg$	5.7 $kgCO_2$

The compensation time for the added embodied energy defined in **3.6.1 Energetic assessment** is calculated using **Equation 3.6**, considering the added primary embodied energy and the yearly primary energy savings for the weighted primary energy factors for district heating from **Table 3.8**. Following this approach, the additional embodied energy related to the renovations, is compensated in 14 years of the building operation due to reduction in the heating losses.

The compensation time for the carbon equivalent emissions follows the same approach. It considers the carbon emissions related to the production of the added materials presented in **Table 6.8**, and the carbon savings from the saved operational energy, considering the emission factors from **Table 3.9**, leading to a compensation time of 21 years.

The economic analysis of the proposed renovation is realised based on the methodology presented in **3.5.3 Economic impact of interventions**. For the proposed renovation, radiators must be dismounted and mounted after the addition of a 20 mm layer of insulation behind the radiator. Two commercial quotes from 2025 in Luxembourg, shows a unit cost in a range from 169 €/radiator to 288 €/radiator for the first service, and from

189 €/niche to 225 €/niche for insulation, without taxes, as shown in **Figure 6.15**. A unit cost of 165.5 €/niche is calculated for the insulation service based on the SIRADOS database from 2023. The lowest commercial quote renovation service is 14% higher than the database reference due to inflationary pressures, increased labour and material costs, and regional market adjustments that have occurred since the original data was published. The comparison also serves as a validation for the obtained values.

The difference between the two commercial offers shows higher values for commercial offer 2 than 1, for both work categories varying between 71% for moving the radiators, and 19% for the insulation of the niche, and 43% for the total work. However, it must be considered that commercial offer 1 is obtained from companies knowing the building and the exact requirements of the service, due to their experience in executing the refurbishment of the pilot room. Therefore, commercial offer 1 is used as reference for further analysis.

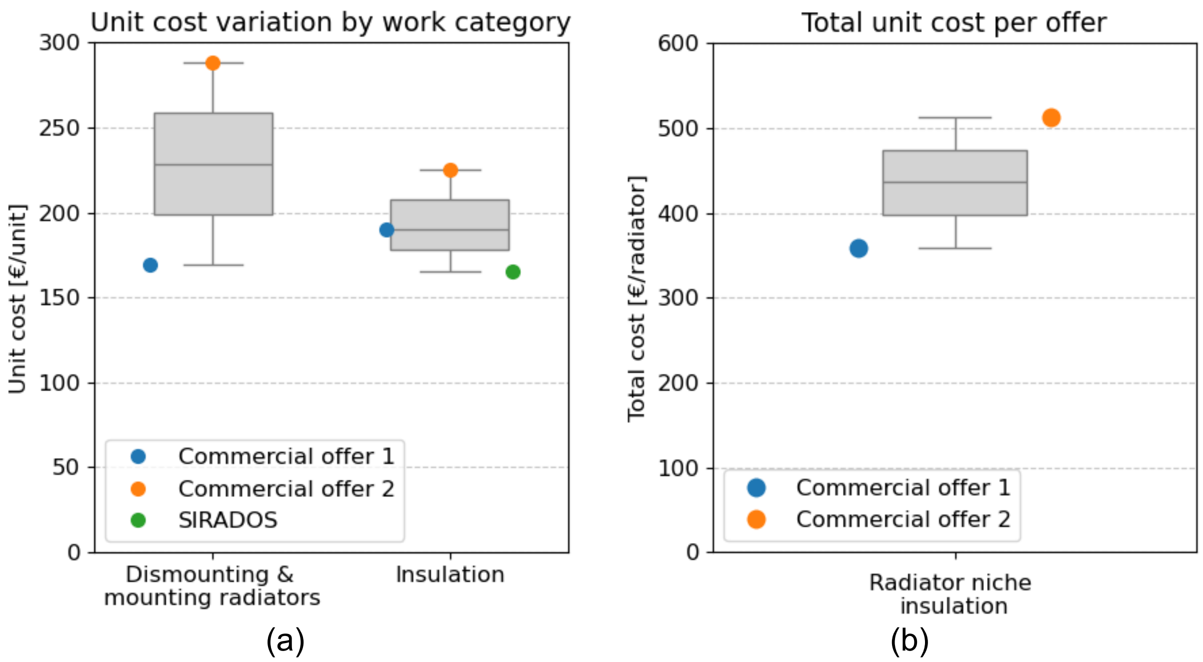

Figure 6.15: Unit costs per radiator niche (1.5 m²): (a) Variation by work category; (b) Total cost per offer

The total investment necessary to add the insulation to the radiator niches in the Central Building is of 218,886 €, according to the values from Commercial offer 1. Considering the unit cost of heat as 0.10 €/kWh, the yearly savings represent 1,537 €/a. The payback time is calculated as 142 years, using Equation 3.10. Financially, this is a very high value and would not be considered as an interesting investment.

6.3.2. Insulation and air tightness of window frame

The thermal model of the Central Building in Building B reveals that 41% of total heat losses occur through the windows. The building is equipped with 507 single-glazed windows featuring aluminium frames. Due to the high thermal conductivity of aluminium, these frames contribute significantly to heat loss and reduce indoor comfort. A number of windows have been found to have warped and distorted panes, thereby preventing them from sliding or closing properly, while their seals show signs of deterioration due to the weather.

In November 2024, five windows facing south-east, in a pilot room were refurbished to improve their air tightness and the thermal transmittance of their frames, estimated as 3 W/m²K, based on local measurements, presented in **Figure 6.19**, and validated by Roulet (2008) [15]. The intervention works included the refitting of the window frames, the replacement of latches and deteriorated seals, and the addition of a layer of insulation to the frame.

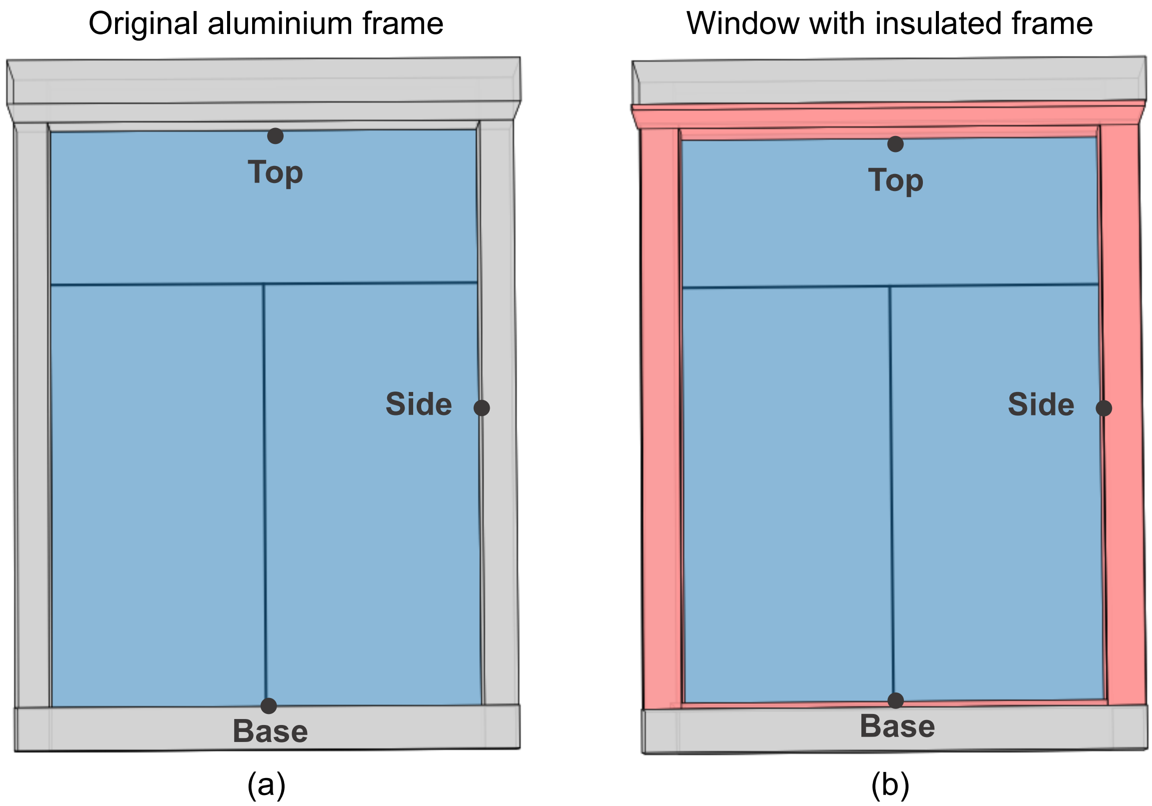

Figure 6.16: Schema of the windows: (a) Original aluminium frame; (b) Original aluminium frame covered with 20 mm of XPS and an aluminium plate (Building B)

Figure 6.17 shows the measures regarding the air tightness of the window frames. A 20 mm layer of extruded polystyrene, commonly known as XPS, was added to the window frame and covered with an aluminium plate matching the rest of the frame, as marked in light red in **Figure 6.16**. The combination of these measures reduces transmission losses and ventilation losses.

Figure 6.17 presents images of the intervention works. A close view in **Figure 6.17 (a)** reveals that, in addition to enhancing the thermal insulation of the frame, this measure also improved the airtightness of the window. The black 2 cm gap visible at the top of the image corresponds to the former opening of an internal blind, which is no longer operational and lately served only as a source of air infiltration. **Figure 6.17 (b)** and **(c)** shows the new seals of the windows, and **(d)** shows that after repairing the panes are aligned. All these measures contribute to reduce infiltration losses.

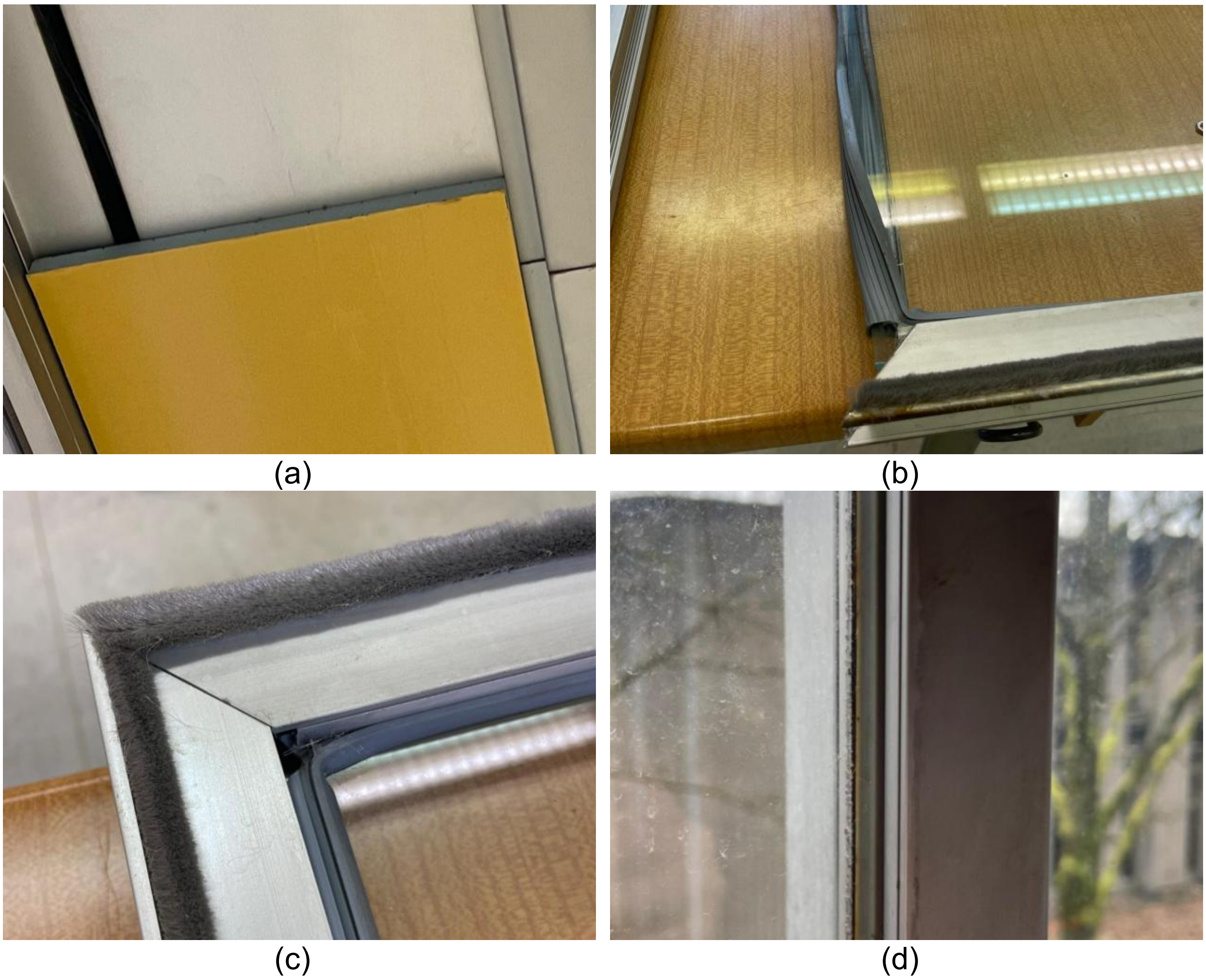

Figure 6.17: Photos window frame insulation. (a) Insulation material added to the top of the window frame, also covering air gap relating to a former internal sun blind; (b) New seals between the glass and the aluminium frame; (c) New window seals between the pane and the frame; (d) Aligned pane frames after renovation (Building B)

The improvement of the thermal resistance of the window frame is calculated based on the thermal conductivity of the extruded polystyrene, known as 0.033 W/mK, following the methodology presented in **3.3.4 Building physics**. The addition of the 0.020 m layer leads to an improved calculated thermal transmittance of 1.1 W/m²K, reduced by more than 63% in comparison to the original frame.

The impact of the implemented measures cannot be directly measured in consumption data, since it is not possible to separate one room from the rest of the building. In order to perform this evaluation, the surface temperatures of the window frames are monitored at three points (Base, Side, and Top), of two window frames (Original and Insulated), during March 2025, as shown in **Figure 6.16**.

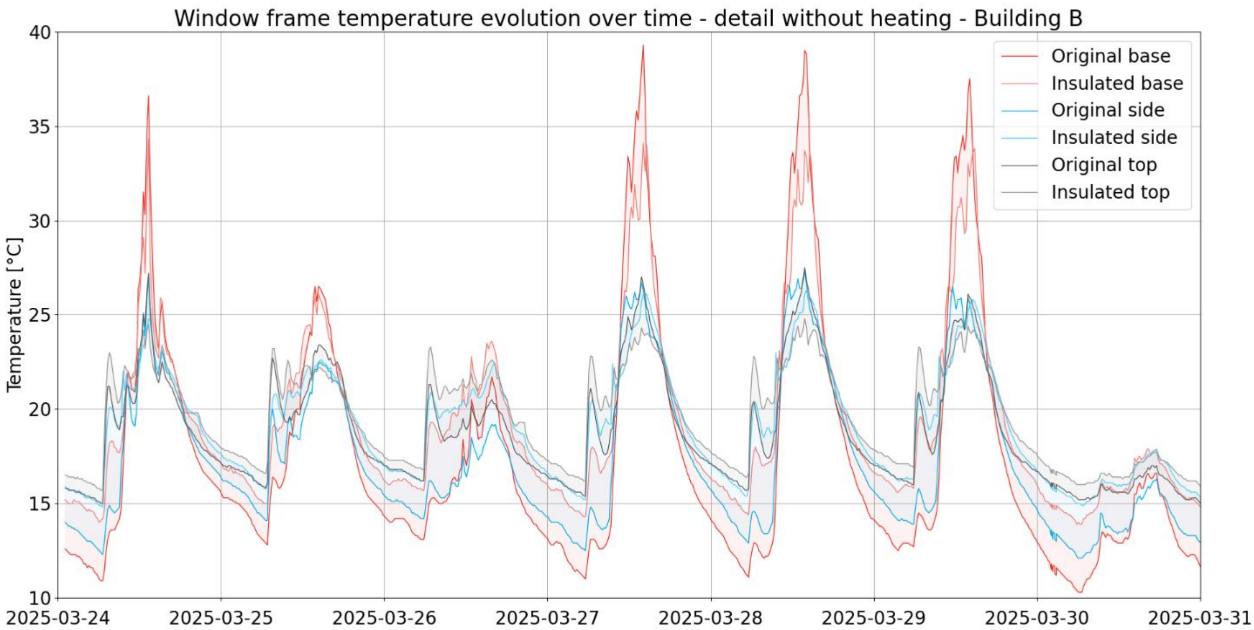

Figure 6.18: Temperature profile measured at the base, side and top of the original window frame, and with the addition of insulation in March/2025 (Building B)

The analysis of the temperature profile of both window frames shows a pattern, as presented in **Figure 6.18** containing the temperature measurements of the two windows during one week from the 23rd until the 30th of March. A vertical gradient temperature is observed over the window frame. The temperature profile is different for each measuring point. The base register higher temperatures during the day, due to the presence of the radiators located below, and the higher incidence of sun in comparison to the rest of the frame. The impact of the sun irradiation is observed from the peaks registered on the 24th, 27th, 28th and 29th of March, in both windows, and especially at the base of the aluminium frame. However, at night, when the heating system is off, the base of the frame also shows the lowest temperatures. The top of the frame shows the smallest variations between day and night, since the hot air tends to go upwards, due to its lower density, maintain this part of the room warmer. The side of the frame discloses a behaviour similar to the base, but with smoother gradients between day and night.

The analysis of **Figure 6.18** also highlights that, due to heating inputs during the day, from the heating system, the solar irradiation and the internal gains, in general, similar temperatures are observed in both windows, since they are submitted to the similar inside setpoints and same outside conditions. It is evident that the heating system compensates for thermal losses in order to maintain the desired indoor temperature. This complicates the quantification of the losses that are occurring during this period. However, during the night, the impact of the additional insulation can be better observed, with similar patterns being registered.

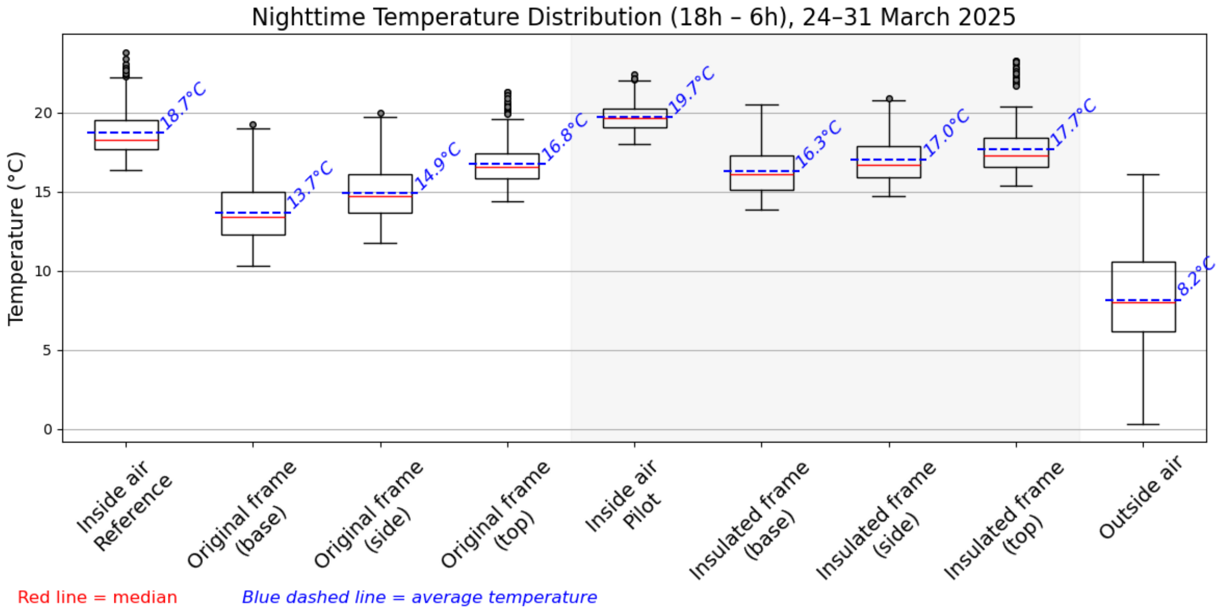

Figure 6.19: Boxplot of outside and inside air and surface temperature of the window frames for the Reference room with original frames, and the Pilot room with insulated frames, during the night, between 24 and 31 March 2025 (Building B)

Figure 6.19 shows the nighttime distribution of air temperature measurements from two rooms, along with the surface temperatures of three specific sections of two window frames (base, side, and top), as illustrated in **Figure 6.16**. The external air temperature data were obtained from Agrimeteo in Luxembourg [114], after been compared with local measurements to ensure their applicability. The first room, referred to as the Reference room, contains the original windows and represents the conditions before the interventions. The second, the Pilot room, is equipped with refurbished windows with insulated frames. Temperature data collected between 24/03/2025 and 31/03/2025 indicate a 1 °C difference in the average indoor air temperature between the Reference and Pilot rooms. Consequently, the temperature gradient between the interior and exterior is 10.5 °C for the Reference room and 11.5 °C for the Pilot room. The window frame in the Reference room shows greater temperature variation between its sections, with an average difference of 3.1 °C between the base and top, compared to only 1.4 °C for the insulated frame. Additionally, the average internal surface temperature of the insulated frame is 1.9 °C higher than that of the original frame. This reduction reflects the lower thermal losses achieved after insulation.

To avoid the influence of the solar, internal, and heating gains in the temperature profile, the analysis of the impact of the added insulation to the window frame is realised based on the data obtained during the night, between 18h and 6h. The difference between the average internal surface temperatures of the original and the insulated frames is calculated as 1.9°C.

Equation 6.2: Heat flux density

$$\dot{q} = \alpha_i \cdot (T_i - T_{si}) = U \cdot (T_i - T_e) \tag{6.2}$$

where:

$\dot{q}$	heat flux density [W/m^2]
α_i	internal surface heat transfer coefficient [W/m^{2}K]
U	thermal transmittance [W/m^{2}K]
T_i	internal air temperature [K]
T_{si}	internal surface temperature [K]
T_e	external air temperature [K]

The thermal transmittances of the window frames are calculated for the three measuring points, based on the night (18h to 6h) average temperatures measured between 24 and 31 March 2025. This calculation is realised based on a simplified energy balance using **Equation 6.2**, and the average temperatures observed at the original and insulated window frames presented in **Figure 6.19**. It considers a one-dimensional steady-state heat conduction, with an internal surface heat transfer coefficient of 8 W/m²K, as an average value for both the original and the insulated frames. **Table 6.9** presents thermal transmittance varying between 1.4 W/m²K and 3.8 W/m²K at the top and the base of the original window frame. The insulated frame registers thermal transmittance varying between 1.4 W/m²K and 2.4 W/m²K, at the top and the base. Based on these results, the average values for the original and insulated frames, calculated from the three measured points, correspond to thermal transmittances of 2.7 W/m²K and 1.9 W/m²K, respectively.

Table 6.9: Calculated thermal transmittances of the original and insulated window frames, based on the night average temperature from between 24 and 31 March 2025, measure between 18h – 6h (Building B)

	Base		**Side**		**Top**		**Average**	
	Original	*Insulated*	*Original*	*Insulated*	*Original*	*Insulated*	*Original*	*Insulated*
U [W/m²K]	3.8	2.4	2.9	1.9	1.4	1.4	2.7	1.9

The average thermal transmittance, presented in **Table 6.9**, calculated for the insulated window frame, using **Equation 6.2**, based on the night temperature measurements is 73% higher than the value obtained following the methodology presented in **3.3.4 Building physics** using the insulating material properties. This is explained by the influence of other interfering factors, such as air infiltration.

Table 6.10: Characteristics of Reference and Pilot rooms (Building B)

	Floor area [m^2]	**Volume [m^3]**	**Envelope surface [m^2]**	**Outside envelope [m^2]**
Reference room	78	233	263	31
Pilot room	64	191	224	26

The improvement in the air tightness of the windows is analysed based on the comparison of two rooms, Reference and Pilot room. The air tightness of the two rooms were evaluated before and after the interventions following the procedures described in **3.3.4 Building physics**. It allows not only the comparison, but also to evaluate the improvement after the refurbishment at the Pilot room. **Table 6.10** shows the characteristics of the analysed rooms.

Table 6.11: Air exchange rate in the Reference and Pilot rooms (Building B)

Air exchange rate	**Before (Jul/2024)**		**After (Dec/2024)**		**Reduction Pilot**
	Reference	Pilot	Reference	Pilot	
Measured n_{50} [1/h] *Normalised at 50 Pa*	32	44	32	32	30%

The air exchange rate values obtained from the blower door test are very high, and this is due to the poor air tightness within the building, between the classrooms. The internal walls have cabling openings between the rooms, in the suspended ceiling. However, from the comparison of measurements realised before and after the refurbishment of the windows, a 30% reduction is observed in the n_{50} value of the Pilot room. Although these values only represent the conditions of the measuring day, the results obtained for the Pilot room after the improvement of the air tightness of the windows was repeated two times. The first measurement was taken in 29/11/2024, and the second on the 13/12/2024, with results showing a difference of only 3% between them. Reference and Pilot were also submitted to decay method analysis, as presented in **3.3.4 Building physics**. However, the results present high variations and were excluded from the analysis.

Monitoring the internal temperatures in the Reference and Pilot rooms also demonstrates the reduction of heat losses. It is challenging to quantify the improvement from the analysis of the day data, when the heat gains compensate for the losses. However, an analysis of the nighttime temperature profiles, in conditions where the heating system is deactivated in both rooms, reveals distinguishing characteristics before and after the renovations.

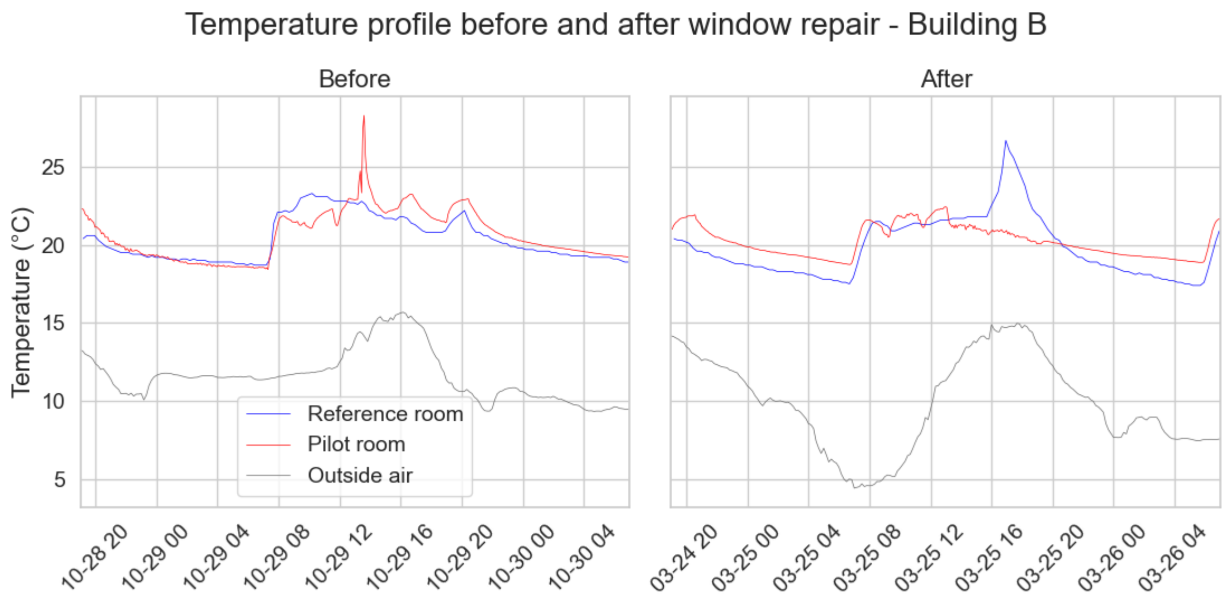

Figure 6.20: Temperature profile before and after window repair and insulation (Building B)

Before refurbishment, similar internal air temperature profiles are observed in both rooms. After the refurbishment, during the night, higher internal air temperatures are registered in the Pilot room in comparison the Reference, as observed from **Figure 6.20**. The peaks temperature in Pilot room at 14h00 CET on the 29/10/2024 refer to solar irradiation falling on the sensor. The peak registered on the 25/03/2025 between 16h00 and 17h00 CET, refers to the impact of extra solar and internal gains.

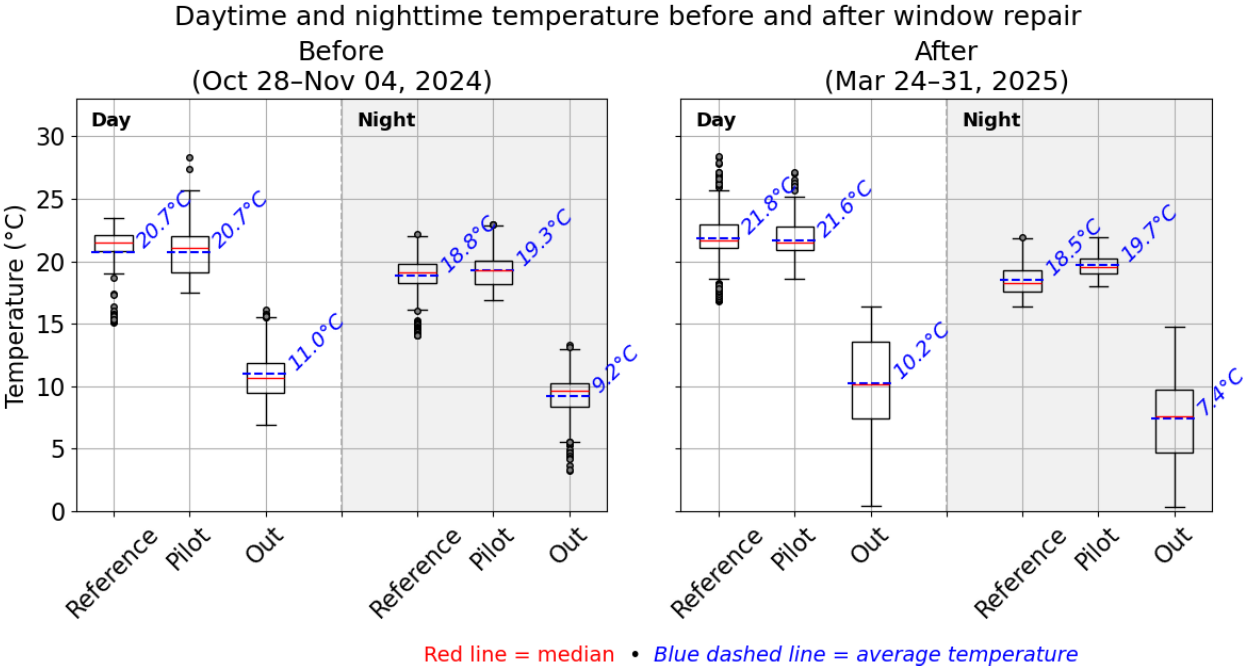

Figure 6.21: Boxplot of the monitored temperatures in the reference and pilot rooms and outside air, before and after window repair and insulation, split into day (7h – 19h) and night (19h – 7h) (Building B)

The analysis of the temperature profile over the monitoring period presented in **Figure 6.21** shows an average of 20.7°C, before the refurbishment of the windows, and 1°C higher after. However, overnight, the average temperatures vary between 18.8°C and 19.3°C at the Reference and Pilot rooms before refurbishment, and 18.5°C and 19.7°C, in the same rooms after refurbishment, as shown in **Table 6.12**. This confirms that during the day, the heating system is compensating the heat losses, to reach the desired temperatures, while during the night, the improvement is observed.

The higher inside air temperatures in the Pilot room, when the heating systems in both rooms are off, is attributed to a reduction on the heat losses resulting from the refurbishment. From the temperature profile, two aspects are observed. The 0.5°C difference between Reference and Pilot room overnight is attributed to the insulation of the radiator niche, which happened in July 2024. After the insulation of the window frames and the improvement of the air tightness of the windows, a temperature difference of 1.2°C is observed between the two rooms.

The variation in the temperature gradient between the two rooms observed in **Figure 6.20** can be attributed to the post-intervention decrease in heat loss, resulting in a higher indoor air temperature. Therefore, this information is used as a reference to estimate the reduction in the heat losses.

Table 6.12: Difference in gradient temperature between Reference and Pilot room during the night from 19h to 7h (Building B)

	Before (Oct/2024)		**After (Mar/2025)**	
	Reference	Pilot	Reference	Pilot
Average inside air temperature (night) [°C]	18.8	19.3	18.5	19.7
Average outside air temperature (night) [°C]	9.2	9.2	7.4	7.4
Gradient temperature between inside and outside air [K]	9.6	10.1	11.1	12.3
Difference in gradient temperature between Reference and Pilot	5%		10%	

As previously stated, the 5% discrepancy noted in **Table 6.12**, prior to the interventions on the windows, is attributable to the enhancement of the thermal resistance of the radiator niche. Consequently, the additional 5% is allocated to the refurbishment of the windows and the enhanced airtightness.

Further energetic and economic analysis are realised considering two scenarios, and two different cases for each. Scenario 1 considers only the refurbishment of the 407 window frames at the classrooms and offices, since the hallways operate with lower temperatures. Scenario 2 accounts for the 507 windows distributed in the Central Building of Building B, including the windows from the circulation areas. Each of these scenarios are analysed comparing Case 1, for the proposed refurbishment of the windows, with Case 2, referring to the full replacement of the windows.

The improved thermal transmittance of the frame after insulation is, as above mentioned, calculated as 2.0 W/m^2K. The energy savings of each case for each scenario are calculated using the thermal model, presented in **5.3 Thermal analysis**, and presented in **Table 6.13**. It considers the final thermal transmittance values for the windows after the insulation of the frame, as 2.7 W/m^2K (for frames with upgraded thermal transmittance of 2.0 W/m^2K representing 30% of the window, while the glass has thermal transmittance of 3.0 W/m^2K), and 0.95 W/m^2K for a new window.

Table 6.13: Reduction in heat consumption per case, per scenario

Heat consumption reduction	**Scenario 1** *407 windows*	**Scenario 2** *507 windows*
Case 1: Frame insulation	55 MWh/a	65 MWh/a
Case 2: Replacement	374 MWh/a	435 MWh/a

The first scenario leads to savings of 55 MWh/a for Case 1, and 374 MWh/a for Case 2. This represents 3% and 24% of the consumption of Central Building in Building B, during the reference year. The second scenario shows savings of 65 MWh/a for Case 1, and 435 MWh/a for Case 2, which represents 4% and 27% of the yearly consumption of 2018.

The information from the environmental product declaration (EPD) in the Ökobaudat database is used to calculate the added embodied energy per window, for the two cases, and the related carbon equivalent emissions [107]. The added primary embodied energy in Case 1, referring to the insulation of the window frame, is presented in **Table 6.14**, while Case 2 concerning the replacement of the existing windows, is presented in **Table 6.15**.

Table 6.14: Primary embodied energy and related carbon equivalent emissions added due to the insulation of one window frame (2 m^2), concerning the product-stage (A1-A3)

Material	Quantity per window	PENRT (A1-A3)	Primary embodied energy	Climate change (A1-A3)	Carbon equivalent emissions
Extruded Polystyrene foam board – 20 mm	0.04 m^3	786.5 MJ/m^3	9 kWh	54.2 $kgCO_2/m^3$	2.2 $kgCO_2$
Anodized aluminium profiles	5 m	696.2 MJ/m	967 kWh	52.1 $kgCO_2/m$	260 $kgCO_2$

Table 6.14 shows that 99% of the added primary grey energy for insulating the window frames, and carbon equivalent emissions, corresponds to the anodized aluminium profiles. The insulation of the window frames entails an added total primary embodied energy of 397 and 495 MWh, for Case 1 - Scenarios 1 and 2, respectively. In terms of carbon equivalent emissions, it corresponds to 107 tCO_2 and 133 tCO_2, for Case 1 - Scenarios 1 and 2.

The intervention proposed the use of aluminium plates to cover the insulation layer to maintain the same appearance observed in the remaining windows. However, the impact of this material on the grey energy content, as well as its low thermal resistance, suggests that alternative solutions may be more suitable.

Table 6.15: Primary embodied energy and carbon equivalent emissions added due to the replacement of one window (3.2 m²), concerning the disposal stage (C3-C4) and product-stage (A1-A3)

Material	Quantity per window	PENRT	Primary embodied energy	Climate change	Carbon equivalent emissions
Treatment and disposal of existing aluminium window	3.2 m^2	175.7 MJ/m^2 (C3-C4)	156 kWh	13.4 $kgCO_2/m^2$ (C3-C4)	43 $kgCO_2$
Aluminium window	3.2 m^2	2,276 MJ/m^2 (A1-A3)	2,023 kWh	177.3 $kgCO_2/m^2$ (A1-A3)	567 $kgCO_2$

The added primary embodied energy refers to the waste processing and disposal of the existing windows, plus the necessary energy to produce the new ones. No further energy content is considered for the existing windows, since they have more than 50 years. **Table 6.15** shows that 93% of the added primary grey energy refers to the production of new windows. The replacement of the existing windows leads to a total added grey energy of 887 MWh and 1,105 MWh, and carbon equivalent emissions of 248 tCO_2 and 309 tCO_2, for Case 2 - Scenarios 1 and 2, respectively.

The compensation time for the added embodied energy and carbon emissions are calculated using **Equation 3.6** and **Equation 3.9**, following the methodology presented in **3.5.1 Energetic impact of interventions** and **3.5.2 Impact of interventions on carbon emissions**. The heat used in Building B is delivered by a district heating connected to a combined heat and power systems, operating with 50% renewable fuels. Therefore the current weighted primary energy and emission factors from **Table 3.8** and **Table 3.9** are used to convert the final thermal yearly savings into primary energy and calculate the corresponding carbon emissions savings. This analysis shows compensation times of 11 to 12 years for embodied energy, and 15 to 16 years for carbon equivalent emissions, for Case 1 - Scenarios 1 and 2. Case 2 shows compensation times 4 years for primary embodied energy, varying between 5 and 6 for carbon equivalent emissions, for Scenarios 1 and 2.

Following the methodology from **3.5.3 Economic impact of interventions**, the economic analysis of the renovations of the windows is divided in two parts. Knowing that all the repairs have an impact on energy savings, the activities are separated between normal maintenance measures necessary for the regular operation of the windows, and the insulation of the window frames to improve their thermal resistance. Furthermore, these are analysed for the two scenarios, and their two cases. **Table 6.16** shows the costs for the different measures.

Table 6.16: Costs for repair and improvement of one window (references: two commercial offers and SIRADOS [109])

Measures	Refurbishment [€/window]		New [€/window]	
	Commercial offer 1	Commercial offer 2	Commercial offer 1	SIRADOS
Dismounting and disposal of existing windows	-	-	185	185*
Repair – sliding sashes and sealing	565	565*	3,212	3,440
Insulation – 2 m² window frame	1,032	561		
Total	**1,597**	**1,126**	**3,397**	**3,625**
** Based on the commercial offer 1, since commercial offer 2 did not include it, and no similar service could be identified within the SIRADOS data base*				

The commercial offer is validated from the comparison with the SIRADOS data base, showing a 6% lower cost for replacing the exiting windows with a new one. The lowest offer for refurbishment of the existing windows represents 33% of the costs associated with the replacement by a new one. It is important to highlight that in commercial offer 1, 35% of the costs for refurbishment are related to necessary repair to ensure that the windows can be opened and closed, and that they do not have unwanted openings. Although such repairs have an influence on the air tightness of the windows, they are merely part of regular maintenance.

The economic analysis compares Cases 1 (insulation of window frames) and 2 (replacement of existing windows) for the two scenarios (407 and 507 windows). It compares the investments for each measure, based on a combination of commercial offer 2, with the financial savings related to the reduction in heat consumption, presented in **Table 6.13**, considering the heat cost as 0.10 €/kWh, according to the energy bills. The results concerning the total investment and the payback time are presented in **Table 6.17**.

The costs for repair are not included in this analysis, as they refer to normal maintenance, and have no direct financial income.

Table 6.17: Economic analysis of the measures to improve thermal resistance and air tightness of the windows

Measures	**Scenario 1** *407 windows*		**Scenario 2** *507 windows*	
	Investment [€]	Payback time [years]	Investment [€]	Payback time [years]
Case 1: Frame insulation **(commercial offer 2)**	228,327	35	284,427	44
Case 2: Replacement	1,382,579	37	1,722,279	40

The results presented in **Table 6.17** show that none of the measures are economically feasible. However, they can be justified as measures to reduce carbon emissions. The lower time to compensate the added embodied energy, would indicate the replacement of the windows as the best option, but two points must be considered in this regard. First, it is important to highlight that the use of Building B in ten years is still not clear, and in case it is dismantled, the new windows would be prematurely disposed. Second, the savings from the replacement of the windows are obtained from simulations. The existing body of literature indicates that the replacement of windows in older buildings may result in significantly reduced savings compared to forecasts. This is due to the necessity for enhanced ventilation to ensure air quality and to prevent issues such as mould growth, which arises as a consequence of the airtightness of the new devices [25].

6.3.3. Inverted roof insulation

An inverted roof is a construction system in which the thermal insulation layer is placed above the waterproofing membrane, rather than beneath it as in traditional flat roof assemblies, as presented in **Figure 6.22**. In the context of existing buildings, it enhances the thermal performance without big interventions in the structure, or disruption of the internal environment. In this configuration, rainwater can infiltrate the insulation layer, which is typically composed of closed-cell extruded polystyrene (XPS) that resists water absorption. Therefore, an appropriate drainage system, including filtration layers, drainage mats, and suitable slope, to ensure efficient water flow away from the insulation and membrane layers, have a direct impact on performance and durability.

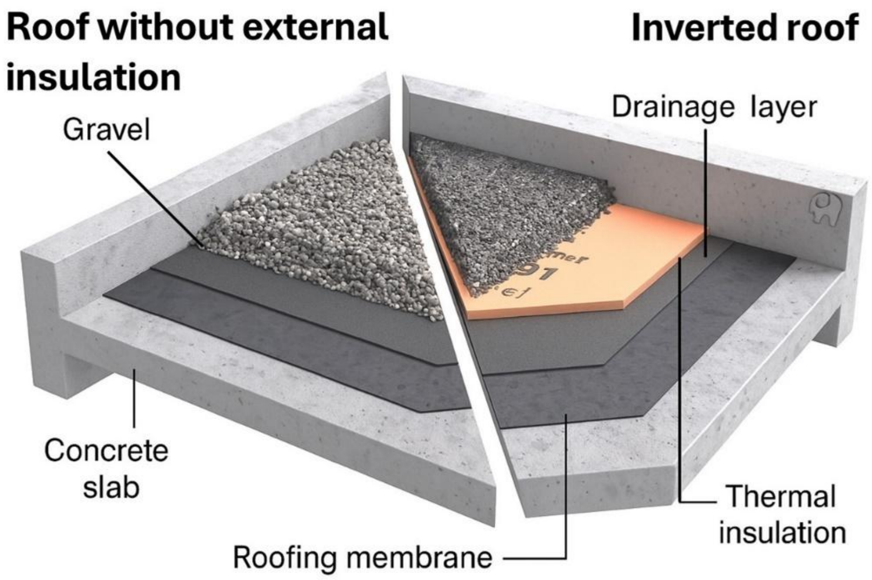

Figure 6.22: Inverted roof concept, with the addition of extruded polystyrene (XPS) insulation board at Central Building (Building B).

Water accumulation within or beneath the insulation layer increases the thermal conductivity of the insulation, reducing its effectiveness of the energy efficiency intervention. Stagnated moisture can cause the degradation of the insulation material in case of freezing and defrosting cycles, besides hydrostatic pressure on the waterproofing membrane, increasing the risk of water ingress through any imperfections or weaknesses, impacting the structure of the building.

The evaluation of such measure is realised for the 5,800 m^2 flat roof surface, with internal insulation, of the Central Building of Building B. Its implementation only requires the temporary removal of the 3 cm of gravel, for the installation of extruded 5 cm polystyrene insulation board incorporated with a polyethylene film and a protective fleece with filtering and draining functions on one side, to improve the thermal resistance and avoid the risks of stagnated water. Such boards have thermal conductivity of 0.035 W/mK. The improvement of the thermal transmittance, as well as the reduction in the heat losses are analysed for three insulation board thicknesses (50 mm, 120 mm and 240 mm). The insulation is added to the existing roof with the measured thermal transmittance value presented in **Table 5.11** of 0.65 W/m^2K.

The energy savings obtained from the implementation of an inverted roof at the Central Building of Building B, for varying insulation thicknesses are simulated using the thermal model of the building. The results in **Table 6.18** show yearly savings from 186 MWh/a to 307 MWh/a for thicknesses varying from 50 mm to 240 mm. It represents between 12%

to 19% of the yearly heat consumption of the Central Building, in Building B, for the reference year (2018).

The yearly carbon savings are calculated considering the savings in the heat energy consumption, following the methodology presented in **3.5.2 Impact of interventions on carbon emissions**. The heat is supplied by a district heating system, with half of the production corresponding to the use of natural gas. The Luxemburgish directive concerning the energy efficiency of buildings define the emission factor as 0.258 kgCO_2/kWh of the final energy, for such system [74].

Table 6.18: Savings in heating energy and carbon emissions with inverted roof insulation

Scenarios	Roof thermal transmittance [W/m^{2}K]	Heating savings [MWh/a]	Yearly heating savings	Yearly carbon emission savings [tCO_2/a]
Roof	0.65	-	-	-
Roof + 50 mm XPS	0.33	186	12%	24
Roof + 120 mm XPS	0.20	259	16%	33
Roof + 240 mm XPS	0.12	307	19%	40

As previously observed, the most significant reduction rates are observed at the thinnest thicknesses. Increasing the thickness of the insulation by 480%, only leads to an increase of 7% on the yearly heating energy savings. However, the compensation time for grey energy and carbon emissions of the varying thicknesses, calculated based on the methodology presented in **3.5.1 Energetic impact of interventions** and **3.5.2 Impact of interventions on carbon emissions** and presented in **Table 6.19**, shows a lower increase. The results show that the grey energy added to the building with the implementation of an inverted roof is compensated in two years for the 240 mm insulation layer. In terms of carbon emissions, the compensation time vary between 1 and 2 years for 50 mm to 240 mm insulation layer. After this period, the simulated carbon savings from 24 tCO_2/a to 40 tCO_2/a are expected.

The economic assessment is realised based on commercial quotes. For the service of removing and storing the existing gravel, improving the drainage system, installing the extruded polystyrene foam boards, covering it with a draining and protective liners, as replacing the gravel, leads to a unit cost of 185 €/m^2 for the 120 mm insulation thickness. The variation in the unit cost due to the change on the thickness is calculated based on the SIRADOS data base, which shows a reduction of 0.115 €/mm of the extruded polystyrene foam.

Table 6.19: Primary embodied energy and related carbon equivalent emissions added due to the inverted roof insulation, concerning the product-stage (A1-A3)

Material	Roof area [m^2]	Insulation thickness [mm]	PENRT (A1-A3) [MJ/m^3]	Primary embodied energy [MWh]	Climate change (A1-A3) [$kgCO_2/m^3$]	Carbon equivalent emissions [$kgCO_2$]
Extruded polystyrene foam board + protection membrane	5,800	50	786.5 + 16.4	90	54.2 + 0.8	20,452
		120		179		42,473
		240		331		80,224

The total investment necessary for installing the inverted roof solution at the Central Building varies from 1,026,310 € to 1,153,040 €. Considering the unit cost of heat as 0.10 €/kWh, the yearly savings represent 18,600 €/a and 30,700 €/a. The payback time is calculated using **Equation 3.10**, and represents 55 years for the scenario with addition of 50 mm insulation board, and 38 years for 240 mm. The high investments and payback times makes this solution not feasible if only considering the financial aspect.

Another important aspect to be considered is the little influence of operation in the actual savings. Conversely to the case of windows, where the simulated values for older buildings are strongly impacted by the need for extra ventilation to ensure air quality, the roof insulation only influences the heat losses. As previously discussed, the thorough implementation of this solution with special attention to an adequate drainage is essential to achieve the expected energy savings and guarantee the durability of the material.

6.4. Integrating renewables

Educational institutions serve as ideal platforms for demonstrating and promoting sustainable practices, fostering awareness and behavioural change among students and staff. Therefore, the strategic deployment of renewable energy solutions in educational buildings represents both an effective carbon mitigation measure and an opportunity to embed sustainability into the core of academic environments.

The reduction in energy consumption of buildings during operation is limited. The adoption of passive measures and the optimisation of operation contribute to reaching low consumption standards. However, for a building to have no carbon emission, the use of energy from renewable sources through the entire life cycle of a building is necessary. This study explores optimisations of the building and its operation in order to reduce their energy consumption, without strongly increasing their embodied energy. This subchapter explores measures regarding the use of renewable energies during the building operation to enhance the reduction in carbon emissions.

Educational facilities, often exhibit high and consistent energy demands due to extended occupancy and intensive use of lighting, heating, and electronic equipment. By incorporating on-site renewable systems such as photovoltaic panels, or replacing fossil fuels by renewable based energy vectors, such as hydrogenated vegetable oil and hydrogen, educational buildings can significantly reduce their carbon emissions.

With the advancement of restrictions concerning greenhouse gas emission gases, low-emission energy vectors are becoming more popular, and suppliers are expanding their availability. Although their prices are usually still higher than traditional fuels, they provide an interesting solution for an easy to implement intervention. Depending on the type of energy carrier, and its properties, it can be used in existing assets without requiring high retrofit investments, for both engines and infrastructure. The challenges it still faces are related to up-scaling and availability.

6.4.1. Photovoltaic panels on school buildings

Over the past years, Buildings C and D installed photovoltaic systems as part of the efforts to reduce the carbon emissions related to the electricity required in their operation, offset electricity consumption and reduce reliance on grid-supplied energy.

In May 2023, Building C started to operate a photovoltaic system composed of 430 monocrystalline modules, with an installed capacity of 159.1 kW_p. In the year 2024 a production of 130 MWh was registered, representing 14% of the yearly energy consumption of the building [118].

A photovoltaic system with 632 monocrystalline modules of 330W and installed capacity of 208.6 kW_p is operating in Building D since April 2021. In average it produces 150 MWh per year, representing 12% of the building consumption.

These on-site systems contribute to the decarbonisation of building operations by reducing grid electricity use, which depending on the region, is still significantly based on fossil fuels. However, while the operational phase of photovoltaic panels is nearly emissions-free, it is essential to account for the embodied energy over the necessary in their manufacturing, transportation, installation, and end-of-life management. **Table 6.20** presents the primary embodied energy content of an average monocrystalline photovoltaic module, calculated based on the Ökobaudat data base [107].

Table 6.20: Primary embodied energy and carbon equivalent emissions content of photovoltaic system per module (1.7 m²), concerning the product-stage (A1-A3)

Material	Module surface [m^2]	PENRT (A1-A3) [MJ/m^2]	Primary embodied energy [kWh]	Climate change (A1-A3) [$kgCO_2/m^2$]	Carbon equivalent emissions [$kgCO_2$]
Photovoltaic system	1.7	3,885	1,835	297	505

The average production of the two studied photovoltaic systems is used to calculate the compensation time. It is simulated based on the avoided electricity from the grid, using the current (1.50) and the previous (2.67) corresponding primary energy factors in Luxembourg, presented in **Table 3.8**. The savings in primary energy consumed from the grid leads to compensation times of 5 years for the current primary energy factor, and 3 years, when adopting the previous factor for the electric mix. The carbon equivalent emitted in the production is compensated in between 4 to 6 years, considering the environmental factor of the electricity mix presented in **Table 3.9**, considering the yearly electricity production of each photovoltaic system to represent the avoided consumption from the grid. Therefore, the yearly carbon savings of Building C is simulated as 48 tCO_2/a, while Building D accounts for 55 tCO_2/a. It represents in average a reduction of 51 $kgCO_2/m^2a$ of photovoltaic plant.

The installation of a photovoltaic power plant with capacities in the same order of magnitude as the installed in Buildings C and D costs 1,065 €/kW_p, based on commercial offers. It is observed that the choice for modules fabricated in Germany increases the installation costs by 7%, in comparison to the Chinese option. Meanwhile, the system with 50 kW_p higher capacity also shows a reduced cost of 5%, due to scale effect.

To assess the potential financial savings of installing a photovoltaic system in a school setting, the analysis considers the avoided cost of purchased electricity, as presented in **Table 3.9**. This value is derived from the school's energy bills and includes not only the direct cost of electricity consumption but also all associated charges. The payback time is then calculated based on the total investment and the avoided grid electricity expenses. According to the methodology outlined in **3.5.3 Economic impact of interventions**, the investment is expected to be recovered within the 4^{th} year.

6.4.2. Hydrogenated vegetable oil in heating boilers

The heating system in Building D consists of three boilers that operate using heating oil, as detailed in **Table 6.21**, in addition to three tanks with a capacity of 30 m^3 each. The analysis of the use of hydrogenated vegetable oil (HVO) to reduce their carbon emissions is realised considering the consumption of Building D during the reference year of 2018. The total production of heat amounted to 3,398 MWh, consuming a total of 343 m^3 of heating oil in the process, over the course of the year.

Table 6.21: Heating boiler list (Building D)

Boiler type	Model	Year of installation	Capacity [kW]
Oil/Gas boiler (low temperature)	Buderus GE615	2009	1,200
Oil boiler (low temperature)	Buderus Omnimat	1984	1,600
Oil boiler (high temperature)	Ygnis WA 100	1975	1,160

The technical files from the Buderus GE615 - Logano GE615, specifies the fuels adapted to the system for each country. In Germany, the heating oil must comply with DIN 51603-1. **Table 6.22** shows the comparison between the fuel properties for heating oil, according to the DIN 51603-1, the HVO according to the EN 15940, and the average values informed by in the technical sheet from TotalEnergies for the HVO100.

With regard to the compatibility of the existing boiler with HVO, it has been determined that, in comparison to heating oil, HVO holds a lower density and viscosity range. This may have implications for the air-fuel ratio, requiring recalibration of the burner for better outputs in terms of efficiency and flue gas emissions. Furthermore, it may impact fuel injection and pump performance, requiring adjustments to nozzle size and pressure levels. The remaining properties either have a positive or no impact in the operation of the system. This is particularly evident in the higher cetane number, which has been shown to enhance combustion due to its superior ignition quality [50].

Heating oil–fired boiler systems are equipped with flame sensors to detect the presence of a flame and ensure safe, reliable combustion. These sensors are typically ionisation rods or UV sensors, both designed to operate over a broad range of flame conditions. When changing to a heating oil with different combustion characteristics, such as the HVO the ignition behaviour of the flame, ionisation properties, and spectral output can change. It is therefore important to verify that the flame sensor is producing a reliable signal and, if necessary, clean, replace, or adjust it. Such checks should be carried out by a qualified heating engineer or technician responsible for the system.

Table 6.22: Comparison of fuel properties

Standard	**Heating oil (DIN 51603-1)**	**HVO (EN 15940)**	**HVO100 (TotalEneries Technical sheet)**
Heat of combustion	42.5 MJ/kg	44 MJ/kg	44 MJ/kg
Density at 15°C	820–860 kg/m³	775–840 kg/m³	780 kg/m³
Viscosity	~2–6 mm²/s [20°C]	1.5–4.0 mm²/s [40°C]	2.9 mm²/s [40°C]
Flash point	≥ 55°C	≥ 70°C	79.5°C
Cetane number	≥ 45	≥ 70	73
Sulphur content	≤ 50 mg/kg	≤ 5 mg/kg	0.4 mg/kg
Oxygen content	0%	≤ 0.5%	nonexplosive
Cold properties (CFPP)	≤ –10°C (–20°C for winter)	≤ –20°C (–30°C for winter)	–25°C (summer and winter)
Ash and water content	Ash ≤ 0.01%, Water ≤ 200 mg/kg	Ash ≤ 0.01% Water ≤ 200 mg/kg	Ash < 0.01% Water < 30 mg/kg
Oxidation stability	≤ 25 g/m³	≥ 20 h (Rancimat method)	6 g/m³ > 20 h

According to the Luxemburgish energy efficiency of buildings directive the carbon emissions of heating oil represents 0.300 kgCO_2/kWh, as presented in **Table 3.9** [74], while following the typical values from the Renewable Energy Directive the emissions of the HVO vary from 0.043 kgCO_2/kWh of the lower heating value for the waste cooking oil, and 0.165 kgCO_2/kWh of the lower heating value for the rape seed oil [57]. Considering this range, a low and high carbon emission savings scenario are established. The replacement leads to savings between 45% (low scenario) and 86% (high scenario) depending on the feedstock. For Building D, the carbon savings per year vary from 459 tCO_2/a in the low saving scenario and 973 tCO_2/a for the high carbon emission savings scenario, while keeping the existing infrastructure. In the case of this school, this is especially positive, since a new facility is being planned, and thus no major investments in the existing building are planned.

The investments required when replacing fuels include verifying the compatibility of the flame sensor with the different combustion characteristics of hydrogenated vegetable oil, and if necessary, replacing it. The higher hydrogen content and improved combustion quality of HVO can increase flame temperature compared to traditional heating oil, requiring adapted sensors. There is a vast variety of these sensors, which need to comply with the burner, with costs varying accordingly. In this analysis a cost of 200 € is considered.

The operational costs increase due to the higher hydrogenated vegetable oil production costs, when compared to the fossil fuel. Conversely, the carbon tax exoneration for the hydrogenated vegetable oil compensates for almost half of the production costs. In March/2025, the heating oil price represented 0.78 €/L, while the hydrogenated vegetable oil 1.03 €/L. In total, this represents an increase of 85,808 €/year in the heating costs, which can be justified by the carbon savings.

6.4.3. Hydrogen in combined heat and power engines for district heating

Buildings B and C are both heated by district heating. Due to their high efficiencies (65% to 85%) and capacity factors (up to 85%), combined heat and power engines are commonly used in such systems. Therefore, the adoption of renewable fuels in such plants play an important role in the energy transition by decarbonising a process. In Luxembourg cogeneration plants are running mainly on wood pellets or natural gas. This study assesses the technical and economic feasibility of retrofitting a combined heat and power cogeneration engine used for district heating, for gradually replacing natural gas by hydrogen.

Ribeiro et al. (2025) analyses the conversion of a natural gas combined heat and power plant in Luxembourg to operate with blending of up to 100% hydrogen. The technical feasibility of converting a natural gas cogeneration engine into a hydrogen-ready system is documented, and such conversions are becoming increasingly widespread. The analysis mainly refers to the compatibility of the material with hydrogen, to resist embrittlement, and in terms of the combustion, strategies to reach high efficiencies while maintaining NO_x emissions below the regulated requirements. The necessary changes apply to the engine, but also to the infrastructure, and are related to the differences between the properties of the two fuels, from **Table 6.23** [60].

Table 6.23: Comparison of the combustion properties of hydrogen and methane. If not specified, values are given at normal temperature and pressure (NTP, i.e., 293.15 K and 1 atm) [60]

Property	Unit	Hydrogen	Methane	References
Density (1 bar, 298 K)	kg/m^3	0.08	0.67	[119]
Lower heating value (LHV)	MJ/kg kWh/kg	120 33.3	50 13.9	[120]
Higher heating value (HHV)	MJ/kg kWh/kg	142 39.4	55.5 15.4	[121][122]
Heat of combustion	MJ/kg_{air}	3.48	2.90	[120]
Adiabatic flame temperature with air	K	2318	2148	[120]
Flame velocity	m/s	2.65-3.25	0.37-0.45	[120]
Diffusion coefficient in air (1 bar, 273 K)	m^2/s	8.5×10^{-6}	1.9×10^{-6}	[123]
Flammability range	volumetric % in air	4-75	4.3-15	[120]
Minimum ignition energy	mJ	0.02	0.29	[120]
Auto-ignition temperature	°C	585	540	[120]
Stoichiometric composition in air	volumetric % in air	29.53	9.48	[120]
Stoichiometric air–fuel ratio	Mass basis	34.12	17.23	[120]
Quenching distance	mm	0.64	2.1	[120]
Research octane number (RON)	-	>130	120	[122][124]
Motor octane number (MON)	-	-	120	[122]

The 88% lower density of hydrogen in comparison to methane at operational conditions, requires more space to provide the same energy content at equal pressure, leading to changes to increase the size of storage and widening of the distribution systems.

Furthermore, the material used in such systems, such as tanks, valves, gas pressure regulators, and pipes must be resistant to the hydrogen embrittlement. The small hydrogen molecule, can diffuse through certain materials, increasing the risk of leakage through joints and mechanical seals. This evaluation is realised considering the material properties, but also depending on the working pressure, as stated by the European Industrial Gases Association (EIGA). According to this report, carbon steel pipes, with a maximum tensile strength of 800 MPa, are adapted to the operation. Concerning stainless steel pipes, austenitic steel is preferable to ferritic or martensitic steel, due to its better corrosion resistance [125]. The wide flammability range, the low ignition energy and the quick diffusion of hydrogen can increase the risk of explosion. Moreover, since the flame is not visible to the naked eye, additional flame and gas detectors must be added for safety reasons [126].

The internal combustion engine also requires changes to adapt to the different properties of hydrogen, to avoid mechanical failures, safety issues, output decrease, and an increase in harmful emissions. Due to the 10 times lower minimum energy required for igniting hydrogen, the ignition system has to be adapted to avoid hot spots in the combustion chamber and issues such as pre-ignition and backfire. Engine knocking can also be a cause and consequence of backfire [127]. To avoid this issue, the combustion can be triggered by a glow plug, a resistance hot wire, or a spark plug which is kept as cold as possible. The spark plugs should not have platinum tips, because platinum acts as a catalyst for hydrogen oxidation [127][128].

Hydrogen can enter the crankcase by leaking through the piston rings on hydrogen-fuelled internal combustion engines. To avoid safety risks linked to the presence of unburnt hydrogen due to its low ignition energy, pressure relief valves must be installed in the crankcase. Furthermore, good ventilation must be ensured to avoid exhaust gases, in the case of a hydrogen engine mainly water vapour, condensing in the crankcase, reducing the effect of oil lubricants [128].

The internal combustion engines use different types of fuel injection to introduce the fuel into the combustion chamber. Central injection forms the air–fuel mixture during the intake stroke and introduces the fuel at the inlet of the air intake manifold. Port fuel injection introduces the fuel into each intake manifold, and the air is injected separately. Direct injection forms the air–fuel mixture inside the combustion chamber and introduces the fuel when the intake valve is closed, which avoids backfiring [128].

In Luxembourg, combustion installations with a nominal thermal output equal to or greater than 1 MW and smaller than 50 MW are classified as median combustion plats, and their emissions are regulated by the “Règlement grand-ducal du 24 avril 2018 relatif à la limitation des émissions de certains polluants dans l'atmosphère en provenance des installations de combustion moyennes”. It establishes a limit for NO_2 emissions of 100 mg/Nm^3 for combustion of natural gas, and 200 mg/Nm^3 for combustion of other fuels in gaseous form [129].

In practice a reduction in NO_x emissions is normally observed for hydrogen–natural gas blending percentages under 30% [130]. Conversely, higher blending rates may lead to an increase in thermal NO_x emissions due to the higher hydrogen flame temperature. The higher hydrogen flame temperature requires adapting the air-fuel ratio for a lean-burn combustion, to lower the process temperature and control the NO_x emissions. The turbocharging system used to force additional compressed air into the combustion chamber, can be adapted to ensure a safe and efficient combustion process [127].

The lean-burn combustion refers to the air–fuel ratio (mass ratio of air to fuel) greater than 1, meaning that combustion takes place with an excess of air. Verhelst et al (2013) shows peak NO_x emissions for a 1.2 ratio. To allow the adoption of mixtures closer to the stoichiometric ratio, and thus improve the efficiency of the system, further reduction in NO_x emissions is achieved through exhaust gas recirculation. Its principle is to reinject part of the exhaust gases back into the cylinder, decreasing the oxygen proportion and slowing down the combustion process. The thermal inertia of exhaust gases reduces the temperature in the cylinders, consequently, reduces the NO_x emissions [131].

The turbocharging system, used to force additional compressed air into the combustion chamber must be adapted to the lean combustion

The adoption of a lean-combustion, and the reduction of the temperature of the process also contribute to increase the quenching distance (the closest a flame can approach to a surface before being extinguished [122]), reducing the risks of emission of carbon oxides, from the evaporation of lubricant oils, and backfire due to flame escape through an open valve [123][128].

The power output of an internal combustion engine increases with an increasing compression ratio. It can be improved when using hydrogen due to its higher-octane number which allows higher compression ratios [123][128]. The compression ratio, which is directly linked to the temperature increase in the cylinder, can be increased due to the higher auto-ignition temperature, to allow better efficiency and greater output [132].

With regards to safety rules for the storage, hydrogen tanks require additional space, as they need to be surrounded by safety zones. In Luxembourg, the Inspectorate of Labour and Mines has established the safety requirements for storing hydrogen, including a 10 m wide and 2 m tall safety zone in which there are no inhabited or busy areas, for storage tanks [133].

The impact of replacing the natural gas by the hydrogen on the carbon emissions of a cogeneration plant depends directly on the production method. In their Global Hydrogen Review 2024, the EIA states that hydrogen production reached 97 Mt in 2023, of which less than 1% was low-emissions. More than 60% of hydrogen is produced from steam methane reforming without carbon capture, use and storage, with carbon emissions varying from 10.7 $kgCO_2/kgH_2$ to 15.9 $kgCO_2/kgH_2$. However, based on announced projects, low-emissions hydrogen could reach 49 Mt/a by 2030, with emissions varying from 3.10-5.90 $kgCO_2/kgH_2$ for steam methane reforming with carbon capture, use and storage, and between 0.8 to 7.1 $kgCO_2/kgH_2$ for electrolysis using renewable electricity from wind turbines and photovoltaics [60][134][135].

In Luxembourg, the current hydrogen consumption in industry, is provided by trucks coming daily from Belgium. However, as stated in **2.3.3 Hydrogen**, with the development of the hydrogen framework in the region, the first plants to produce hydrogen from electrolysis, in addition to its transmission and distribution, is expected to start operations from 2027 onwards. Therefore, the analysis of the impact of replacing natural gas by hydrogen on the carbon emissions of heat production in combined heat and power plants feeding into the district heating system is realised based on the electrolysis emissions.

The reduction in carbon emissions is not linearly related to the volume of hydrogen added to natural gas for combustion due to several interrelated physical, chemical, and energy factors. In the technical report of the THyGA Project, Leicher et al. (2021) analyses the relation between the carbon emission reduction for the increasing volumetric concentration of hydrogen in the blend. A mixture with 50% hydrogen concentration leads to a 24% reduction in the carbon emissions, and only 55% reduction is obtained from a mixture with 90% hydrogen volumetric concentration [136]. Therefore, the further analysis is realised considering the use of pure hydrogen, for the scenario of the full transition.

The heat consumption of Buildings B and C in 2018 (reference year) is 2,347 MWh/a and 1,937 MWh/a, respectively. Assuming the INNIO Jenbacher system used by Riberio et al. (2025) as a reference for this analysis, the thermal efficiency of the system operating with natural gas is 51.5% and it reaches 53% when switching to hydrogen. The carbon emissions for both scenarios are calculated considering the amount of natural gas and hydrogen necessary to produce the required output, based on the thermal efficiencies. These quantities are multiplied by the carbon emission factors related to the combustion of natural gas and the renewable energy source used in the electrolysis production. Heat is supplied by district heating systems, as detailed in **Table 5.3**. Since half of the produced heat comes from natural gas, the emission factor applied in this analysis for natural gas combustion is 0.258 $kgCO_2/kWh$, as specified in **Table 3.9**, based on the Luxembourgish directive on building energy efficiency [74]. For the hydrogen two average emission factors for electrolysis from wind and photovoltaics were adopted, 0.88 $kgCO_2/kgH_2$ for a low emissions case scenario and 2.21 $kgCO_2/kgH_2$ for a high emissions case scenario [135].

Table 6.24: Analysis of yearly carbon emission savings based on the consumption of the reference year (2018)

<table>
<tr><th></th><th>Fuel</th><th>Yearly heat consumption [MWh]</th><th>Total η [%]</th><th>Thermal η [%]</th><th>Carbon emission factor</th><th>Emissions [$kgCO_2$]</th><th>Savings [$kgCO_2$] [%]</th></tr>
<tr><td rowspan="3">Building B</td><td>Natural Gas</td><td rowspan="3">1,174</td><td>93.5%</td><td>51.5%</td><td>0.258 $kgCO_2/kWh$</td><td>323,811</td><td>-</td></tr>
<tr><td>H_2 - Low</td><td rowspan="2">93.0%</td><td rowspan="2">53.0%</td><td>0.88 $kgCO_2/kgH_2$</td><td>33,346</td><td>290,465
90%</td></tr>
<tr><td>H_2 - High</td><td>2.21 $kgCO_2/kgH_2$</td><td>83,743</td><td>240,068
74%</td></tr>
<tr><td rowspan="3">Building C</td><td>Natural Gas</td><td rowspan="3">969</td><td>93.5%</td><td>51.5%</td><td>0.258 $kgCO_2/kWh$</td><td>267,244</td><td>-</td></tr>
<tr><td>H_2 - Low</td><td rowspan="2">93.0%</td><td rowspan="2">53.0%</td><td>0.88 $kgCO_2/kgH_2$</td><td>27,520</td><td>239,723
90%</td></tr>
<tr><td>H_2 - High</td><td>2.21 $kgCO_2/kgH_2$</td><td>69,114</td><td>198,130
74%</td></tr>
</table>

The results from the analysis of the yearly carbon emission savings in Buildings B and C related to the replacement of natural gas by hydrogen in combined heat and power plants in district heating is presented in **Table 6.24**. The results show the importance of considering the carbon emissions over the entire chain. The impact of using hydrogen produced by electrolysis from renewable sources have a broad range impact, with a reduction from 74% to 90%. The low and high scenarios only consider the use of renewable electricity, but the factors vary with regard to the emissions related to the production of the systems.

With the increase in the renewable shares in the energy mix, and the adoption of more sustainable practices, there is a tendency to reduce the carbon emissions related to the hydrogen production, with the low scenario becoming the reference.

Ribeiro et al. (2025) analysed the economic feasibility of converting a gas combined heat and power plant in Luxembourg to operate with hydrogen, as presented in **Figure 6.23**, under the three following scenarios [60]:

- The "Business as Usual" scenario assumes that no changes in the power plant operation are made. Therefore, the plant continues running on natural gas.
- The "Retrofitting for H_2" assumes that the existing engine is adapted to work with hydrogen and natural gas blends or pure hydrogen.
- The "New engine for H_2" assumes that the existing engine is replaced by a different model to work with hydrogen and natural gas blends or pure hydrogen.

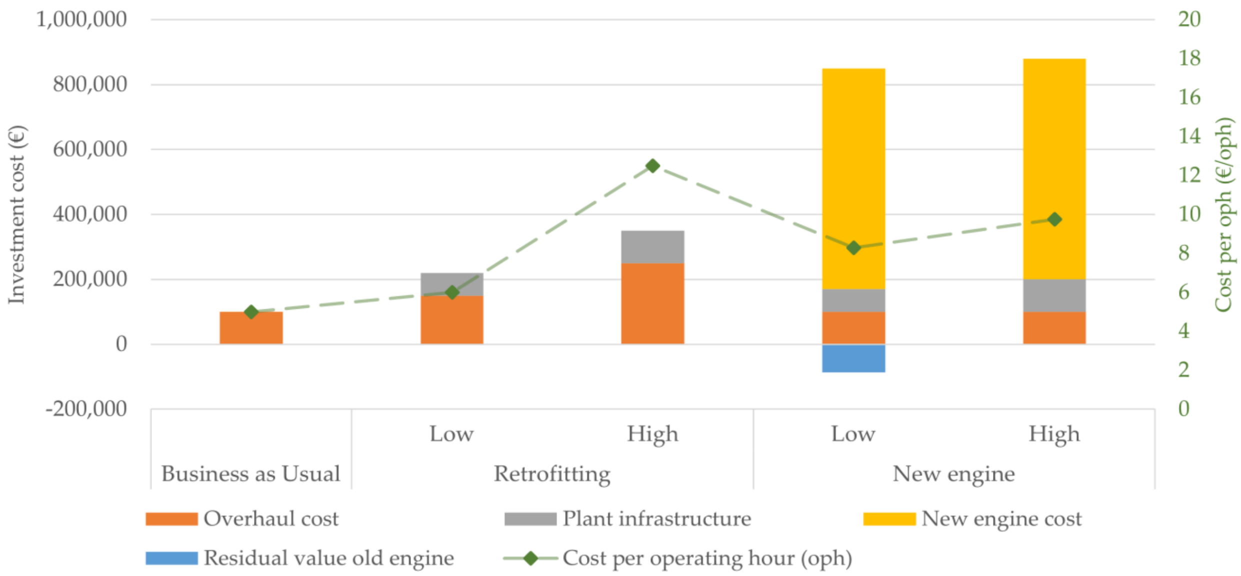

Figure 6.23: Investment costs of the three analysed scenarios. The "Low" and "High" categories refer to the range of the investment. For the "Retrofitting" and "New engine" scenarios, the cost per operating hour is computed with respect to the "Business as Usual" scenario without considering fuel costs

The study shows that although it is already technically feasible to retrofit cogeneration engines, or even buy hydrogen ready new engines, it is still not economically accessible. The costs to convert the existing infrastructure into hydrogen ready is still higher than maintaining the business-as-usual scenario. In terms of investment, besides the 50% to 150% higher overhaul costs for the retrofitting, further 70% to 100% infrastructure costs are added, in comparison to business as usual. The same is observed for replacing the existing besides the costs for the new engine, the plant still needs to undergo maintenance costs, and adapt the existing infrastructure, especially with regards to safety measures.

The operational costs also see an increase, due to the higher hydrogen prices. In the first semester of 2025, the E-Bridge green hydrogen price evolution database registered a hydrogen cost of 6 €/kgH_2 or 181 €/MWh, in comparison to 35 €/MWh for natural gas [137][138]. The green hydrogen costs and selling prices from hydrogen valley are also presented in **Figure 6.24**, showing that more than 30% of the projects have production costs between 4 and 6 €/kgH_2. While 25% of the projects present selling prices above 10 €/kgH_2, most of them are between 4 and 6 €/kgH_2 [139].

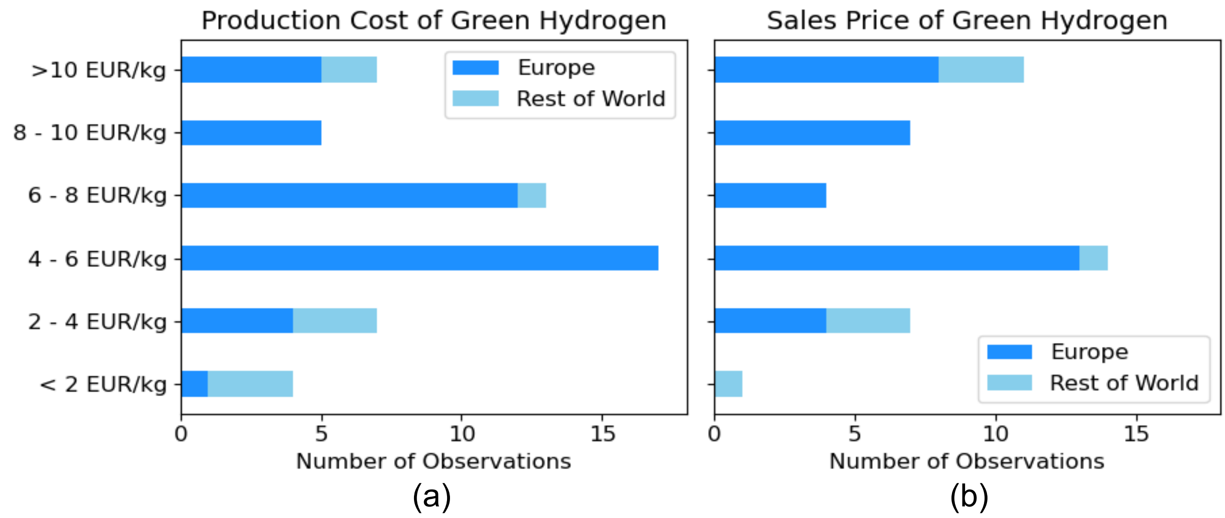

Figure 6.24: Hydrogen (a) production costs and (b) sales price in hydrogen valley projects (based on [139])

Considering the necessary investments and the current 80% lower costs for natural gas, the financial feasibility depends on the fuel price, with investments only representing between 3% to 6% of the yearly operational costs, for the retrofitting low and high scenarios. The comparison of unit costs per kWh produced under the business as usual and the low retrofitting and high new engine scenarios is presented in **Table 6.25**.

The analysis of **Table 6.25** shows a 0.15 €/kWh gap between the hydrogen scenarios and the business-as-usual operating with natural gas, mainly related to the fuel price. Historical data from E-Bridge, shows that in November 2022 the average cost of green hydrogen represented 11 €/kgH_2 or 330 €/MWh [137]. This represents a 45% drop between November 2022 and May 2025, and indicates the impact of the investments in upscaling for reaching competitive prices for the renewable fuel. However, for these scenarios to become competitive with natural gas, hydrogen should cost between 1.2 €/kgH_2 and 1.3 €/kgH_2, which is still not a reality, according to the Clean Hydrogen Partnership statistics regarding the hydrogen valley projects [139].

Table 6.25: Comparison of unit costs per kWh produced under three scenarios

Yearly costs	Scenarios	Operational hours [h/a]	Energy production [MWh]	Investment [€/oph]	Fuel cost [€/MWh]	Unit cost [€/kWh]
Methane	*Business-as-usual*	4900	5,200	5	35	0.04
Hydrogen	*Retrofitting Low*			6	181	0.19
	New engine High			10	181	0.19

The average production costs of hydrogen in the year 2023 is composed mainly by capital expenditure and electricity costs, representing 57% and 40%, respectively [140]. Therefore, to reach the aimed hydrogen prices, efforts must relate do economies of scale for electrolysers and renewable electricity production.

Further competitiveness is added through carbon emission taxes for energy production using natural gas. However, for the 7 €/MWh increment, defined in the Energy Taxation Directive from July 2021, the replacement by hydrogen is still not feasible for prices above 1.6 €/kgH_2.

6.5. Interventions outcomes

The interventions proposed and analysed in Step 3 build directly upon the insights gathered in the previous phases of the framework. The behavioural approach (Step 1) revealed that building users and managers are generally motivated to engage in pro-environmental actions but face practical barriers such as limited control, resource constraints, lack of incentives, and unclear sustainability indicators. The energy audit (Step 2) provided a complementary technical diagnosis, highlighting low performances in electrical, identifying high baseload consumption, and pointing to operational schedules not aligned with actual use. The detailed analysis of the thermal consumption also indicated opportunities for pinpointed renovations. Together, these findings created the foundation for developing targeted interventions to address both behavioural and technical dimensions of energy and carbon reduction.

The measures proposed in Step 3 were grouped into four categories: reduced operational modes, sufficiency measures, renovations, and renewable energy integration. Each category addresses a different level of investment, balance of embodied energy and carbon, operational impact, and user acceptance.

Reduced operational modes are interventions applied during unoccupied periods that require no energetic or financial investments. Their effectiveness depends on adapting technical installations to actual building use, avoiding unnecessary consumption during evenings, weekends, and holidays. Results show that such measures can reduce overall energy consumption by up to 4%, without affecting user comfort. Successful implementation requires clear operational plans, trained staff, and verification to ensure compliance.

Sufficiency measures target technical operations during occupied periods. By aligning system outputs, such as lighting levels or ventilation rates, with real needs, oversized operations can be avoided. Because they are implemented while the building is in use, these measures require careful calibration to ensure user comfort, alongside awareness campaigns to improve acceptability. The results indicate that sufficiency strategies can reduce energy consumption and carbon emissions by up to 7%, again without the need for investment.

Renovation measures provide the largest technical potential, with energy savings of up to one-third of the overall consumption. These include improving insulation of radiator niches, window frames, and roofs. However, their feasibility is often constrained by the need for financial investment, and the balance between the added embodied energy and carbon, and the savings during operation. The analysis indicates that the additional embodied carbon from such interventions may take between 1 and 21 years to be offset by operational savings before yielding a net positive carbon balance.

In the case of the swimming pool in Building C, **Figure 6.25**, illustrates the power profiles of the filtration pumps and ventilation systems before and after the implementation of reduced operational modes and sufficiency measures. The introduction of reduced operational modes during weekends and school breaks resulted in savings of 12 MWh/a, without any negative impact on users. In addition, the sufficiency measure proposes to close the swimming pool between the Christmas and Carnival breaks, combining a four-week holiday period with the examination period. This measure generated savings of 20 MWh/a in electricity over the eight-week period. When combined with the reduced operational modes, the total savings reached 32 MWh/a of electricity and 128 MWh/a of heat. Together, these measures represent a 10% reduction in carbon emissions, with the heat savings achieved by emptying the swimming pool during the closure.

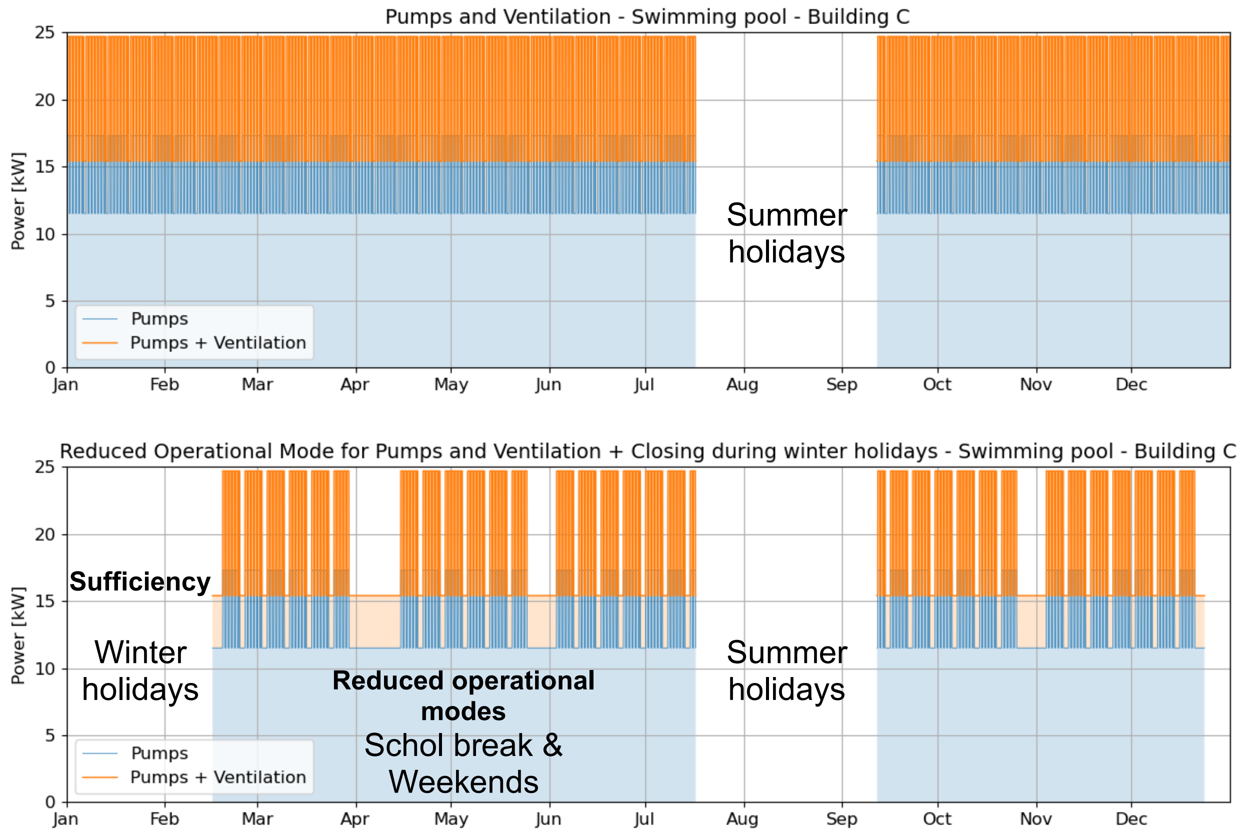

Figure 6.25: Power profile distribution over the year before and after the adoption of reduced operational modes and sufficiency measures at the swimming pool (Building C)

In Building B, the combined effect of reduced operational modes (lowering the heating to 10 °C during winter holidays and closing existing sun blinds overnight), sufficiency measures (mechanical ventilation and lighting), and targeted renovation (inverted roof with 24 cm insulation) resulted in savings of 64 MWh/a of electricity and 407 MWh/a of heat. Overall, these interventions achieved a 32% reduction in carbon emissions.

Renewable energy integration does not directly reduce energy consumption but significantly lowers carbon emissions by substituting fossil-based energy sources.

Photovoltaic systems require upfront investments and carry an embodied carbon footprint, yet they typically achieve both financial and carbon payback within 4 to 5 years. In contrast, replacing fossil fuels with low-carbon alternatives such as hydrogenated vegetable oil (HVO) or hydrogen in cogeneration engines involves lower initial investments for building managers but often results in higher operational costs. The effectiveness of these fuel-switching measures further depends on strict due diligence regarding feedstock sourcing and production processes, as well as the maturity and stability of their respective markets. At the same time, the regulatory and technological frameworks for both HVO and hydrogen are still under development, defining clear control rules, and with increasing support to ensure their continued integration into the energy system.

Overall, the results demonstrate that interventions with no financial investment, such as reduced operational modes and sufficiency measures, can yield immediate and measurable results. In contrast, renovation and renewable integration strategies provide further carbon reductions but require careful consideration of financial feasibility and embodied energy implications.

These findings emphasise the compromise between measures that directly reduce operational energy consumption and those that adapt to the technical limitations of buildings, for example where full electrification remains challenging. The proposed interventions contribute to the energy transition while ensuring effective use of resources and maximising overall impact. The analysed interventions contribute to the energy transition while ensuring effective use of resources and maximising overall impact.

Finally, the results of the energy- and carbon-savings interventions (Step 3) represent the basis for the performance assessment (Step 4), where the effectiveness of the proposed measures is quantified, monitored, and compared. This final phase allows for the evaluation of savings, the identification of opportunities for refinement, and the continuous improvement of both behavioural and technical strategies, ensuring sustainable reductions in energy consumption and carbon emissions.

7. Performance assessment

This chapter corresponds to Step 4 of the Framework presented in **Figure 3.1**, and summarises the performance assessment of the measures discussed in **6 Energy- and carbon-saving interventions**, concerning the existing educational buildings used in this study. The study explores key indicators related to these interventions, including the definition and implementation of reduced operational modes, the role of sufficiency measures, strategies for building renovations, and the integration of renewable energy systems. Together, these discussions provide a structured approach for achieving significant energy savings and advancing the transition to low-carbon educational buildings.

Table 7.1 provides an overview of the simulated and achieved reductions in energy consumption and carbon emissions, considering the added embodied energy, and the economic aspects of each intervention. This allows to evaluate and compare the effectiveness of different measures and establish performance indicators.

The results presented in **Table 7.1** show that the group of measures, here denominated as reduced operational modes, which require neither energetic, nor economic investments, led to savings of up to 4% of the overall consumption. The only requirement to achieve such measures is adapting the operation of technical facilities to the real needs, avoiding unnecessary heat losses and energy consumption. It requires a good understanding of the technical installations and the role of each activity, enabling building managers to reduce them to the minimum during empty periods. To enable implementation, a clear and simple plan must be available, and staff need to be trained. Finally, to ensure their effectiveness, at least during the establishment of the plan, it must be verified and validated. Such measures have no impact in user comfort, since they are implemented during empty periods.

The sufficiency measures also refer to intervention in the operation of technical facilities of the building, but these are implemented while the building is used. Therefore, to assess if the approach has a negative impact the on comfort of the building users, it requires the analysis of the real needs, and careful implementation. Furthermore, to improve acceptability, raising awareness among users is essential. The analysed interventions led to up to 7% reduction in the energy consumption and carbon emissions, without requiring any energetic or financial investment.

Table 7.1: Summary of energy- and carbon-saving interventions

Measure	Energy				Carbon				Economic			Indicator
	Primary embodied energy [MWh]	Yearly savings [MWh/a]	Reduction in specific consumption [kWh/m²a]	Energy compensation time [years]	Emissions [tCO_2]	Yearly savings [tCO_2/a]	Reduction (Ref 2018) [%]	Carbon compensation time [years]	Investment [€]	Yearly savings [€/a]	Payback time [years]	Avoided carbon cost [€/$kgCO_2$]
Reduced operational modes												
Swimming pool - optimization of systems operation during unoccupied periods [Building C]												
Pumps	-	7.5	0.3	-	-	3	1%	-	-	2,625	-	0.95
Mechanical ventilation	-	4	0.2	-	-	1.5	0.4%	-	-	1,400	-	0.95
Winter holidays [Building B]												
Heat to 15°C – 9 days	-	27	1.1	-	-	3	2%	-	-	2,700	-	0.78
Heat to 10°C – 9 days	-	41	1.7	-	-	5	3%	-	-	4,100	-	0.78
Closed sun blinds during night (Scenario 2 - 507 windows) [Building B]												
Current status	-	59	2.5	-	-	8	4%	-	-	5,918	-	0.78
Repair & add sun blinds	161	33	1.4	8	36	4	2%	8	90,156	3,300	27	-8.09
Sufficiency												
Mechanical ventilation [Building B]												
Auditoriums	-	24	0.8	-	-	9	2%	-	-	8,400	-	0.95
Conference room	-	9	0.3	-	-	3	1%	-	-	3,150	-	0.95
Lighting [Building B]												
Common areas	-	31	1.0	-	-	11	3%	-	-	10,850	-	0.95
Swimming pool - winter holidays (2 months) [Building C]												
Winter - electricity	-	20	0.9	-	-	7	2%	-	-	7,000	-	0.95
Winter - heat	-	128	6.5	-	-	17	7%	-	-	12,800	-	0.78

Table 7.1: Summary of energy- and carbon-saving interventions

Measure	Energy				Carbon				Economic			Indicator
	Primary embodied energy [MWh]	Yearly savings [MWh/a]	Reduction in specific consumption [kWh/m^{2}a]	Energy compensation time [years]	Emissions [tCO_2]	Yearly savings [tCO_2/a]	Reduction (Ref 2018) [%]	Carbon compensation time [years]	Investment [€]	Yearly savings [€/a]	Payback time [years]	Avoided carbon cost [€/kgCO_2]
Renovation												
Insulation [Building B]												
Radiator niche	136	15	0.7	14	41	2	1%	21	218,886	1,537	142	-
Window repair and insulation	495	65	2.8	12	133	8	4%	16	284,427	6,500	44	-
Window replacement	1,105	435	18.5	4	309	56	27%	6	1,722,279	43,500	40	-5.11
Inverted roof - 50 mm	90	186	7.9	1	20	24	12%	1	1,026,310	18,600	55	-3.83
Inverted roof - 240 mm	331	307	13.1	2	80	40	19%	2	1,153,040	30,700	38	-2.68
Integration of renewable energy sources												
Photovoltaic panels [Building C & D]												
Building C	789	-	-	4	217	48	14%	5	169,442	45,500	4	1.10
Building D	1,159	-	-	5	319	55	12%	6	222,159	52,500	4	1.31
Hydrogenated Vegetable Oil in heating boilers [Building D]												
Building D	-	-	-	-	-	459	45%	-	600	-85,808	-	-0.19
						873	86%					-0.10
Hydrogen in Combined Heat and Power engines for District Heating [Building B & C]												
Building B	-	-	-	-	-	240	74%	-	-	-119,227	-	-0.50
						290	90%					-0.41
Building C	-	-	-	-	-	198	74%	-	-	-145,275	-	-0.73
						240	90%					-0.61

The measures related to renovations demonstrate a higher energy- and carbon-saving potential, reaching up to almost one third of the overall consumption. However, they also require energetic and financial investments, which reduces their positive impact, and very often impose barriers for implementation. While the pinpointed renovations require lower financial investments, the added embodied carbon of this measure takes up to 21 years to be compensated by the savings during operations, and start generating a net positive impact in terms of carbon emissions.

The last group of measures refer to the integration of renewable energy to the building operation. They do not directly lead to reductions in the energy consumption, but due to their lower carbon footprint, they represent an important reduction in the overall carbon emissions. However, in the case of photovoltaic panels, besides the added grey energy, it requires initial financial investments, which are compensated overtime by the reduction in the energy bill. Conversely, the replacement of fossil fuels represents lower investments, and higher operational costs, which in the context of this study is compared to carbon emission costs.

7.1. Energetic

Among the proposed groups of intervention measures, the first three (reduced operational modes, sufficiency and renovations) lead to energy savings. The first two refer to refined operations, while renovations require energetic investments, in terms of embodied energy. Therefore, in this energetic assessment they are analysed separately.

The reduced operational modes and the sufficiency measures are both related to adapting the energy consumption to the real needs. The first mode refers to defining operational set-points for the technical installations for the empty periods, when the building is not used. These operational settings only consider the need to avoid damages in the building structure, and the retake time, to ensure that the building is ready to offer comfortable conditions for its users, once it is in use. As per the sufficiency measures, they refer to adapting the operation of technical installations, to achieve comfortable conditions for users, since they are implemented in periods when the building is occupied, without overconsuming. Since comfort is a subjective concept, this measure benefits from a combined behavioural approach to improve acceptability.

Figure 7.1 presents the specific and annual savings in electrical and thermal consumption for the intervention measures described in **6.1 Reduced operational modes** and **6.2 Sufficiency**.

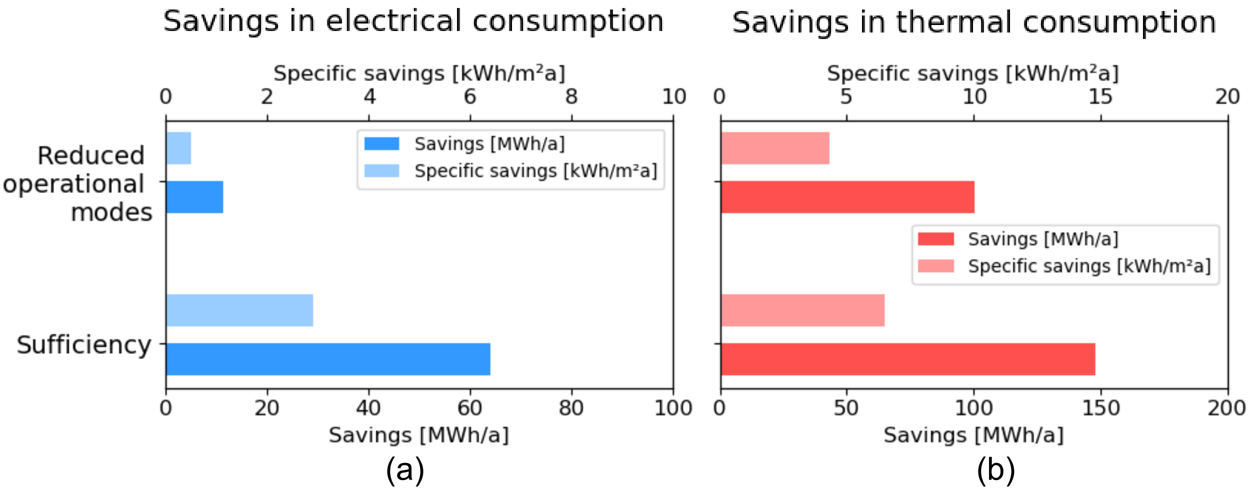

Figure 7.1: Savings in specific and total (a) electrical and (b) thermal consumption of all measures from the reduced operational and sufficiency group

Although the energy audit conducted (following the flowchart in **Figure 5.1**) suggested greater opportunities for reducing electricity consumption, the results in **Figure 7.1** reveal that the implemented measures yield more than three times the savings in thermal consumption compared to electricity. This highlights the value of the proposed approach in guiding targeted efforts, while also emphasising that all energy-saving opportunities should be considered. None of these analysed interventions require financial or energetic investment. Their implementation does not require extra resources, and only depends on initial evaluation to identify opportunities and adapt the operational procedures, monitoring to ensure that it is correctly executed, and training of the responsible staff.

The renovation measures consist in adding extra embodied energy to the building, to improve thermal resistances and air tightness, and consequently reduce energy consumption. Their implementation usually depends on the approval from different parties in the complex stakeholder chain involved in education buildings in Luxembourg.

Figure 7.2 shows the added primary embodied energy, in light red, related to the renovations, and in light green, the final operational yearly savings resulting from such measures. The lowest embodied energy input refers to the inverted roof solution, with 50 mm of insulation, accounting for 90 MWh, leading to yearly savings in terms of final energy of 186 MWh/a. The added primary embodied energy for the insulation at radiator niches, is only 51% higher, however, the yearly savings are 92% lower.

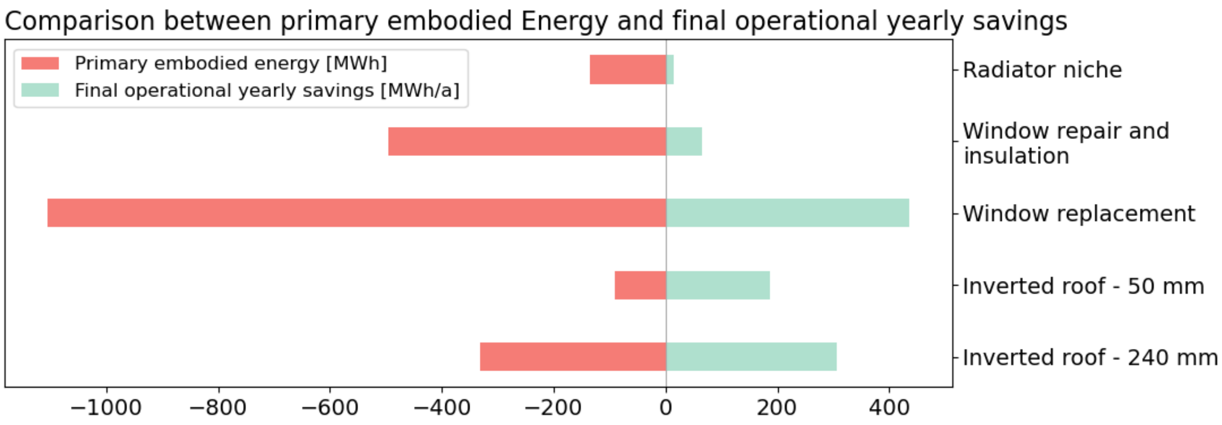

Figure 7.2: Comparison between added primary embodied energy (light red) and the resulting final operational yearly savings for renovation interventions (light green)

On the other edge is the windows replacement, representing an additional primary embodied energy of 1,105 MWh, with related yearly final energy savings simulated as 435 MWh/a. The challenge of replacing windows in buildings with no mechanical ventilations, is that the increased air tightness may lead to higher uncontrolled ventilation rates needs to ensure air quality, leading to negative impacts on the actual operational energy savings. Therefore, although such intervention presents an important simulated potential, in practice it is limited to user behaviour.

The renovation measure with lowest compensation time is the inverted roof, taking 1 to 2 years to recover the added embodied energy, through the operational savings, according to the insulation thickness. The highest compensation times are 14 years and it refer to the radiator niche insulation and 12 years for the window repair and insulation. Material changes may lead to better performances and must be considered in further evaluation.

Over the analysed period, changes in specific operational energy consumption were observed for both electricity and heat. Regarding electricity, all buildings recorded a decrease compared to their 2018 performance (reference year). Buildings A and B achieved reductions of 29% and 30%, respectively, while Building D saw a 15% decrease between 2018 and 2024. Building C maintained a relatively stable electricity consumption, with only a 2% reduction over the same period. This shows the impact of the implemented interventions measures.

With regard to heat consumption, data is only available for Buildings B and C for 2024. The evaluation of the remaining two buildings is conducted on the basis of the most recent data available, specifically 2021 for Building A and 2023 for Building D. Building A experienced an 11% increase in heat consumption between 2018 and 2021, largely due to higher ventilation rates required after the pandemic. Building C also saw a 2% rise between 2018 and 2024. In both cases, meteorological conditions played a role, with heating degree days 14% higher in 2021 and 6% higher in 2024 compared to 2018, as observed in **Table 3.6**. In contrast, Buildings B and D recorded reductions of 19% and 20% in 2024 and 2023, respectively, regardless of climatic variations.

When normalising consumption to neutralise meteorological influence, all buildings show a net improvement in heat efficiency: reductions of 3% for Building A, 22% for Building B, 2% for Building C, and 20% for Building D over the analysed period.

These trends highlight the tangible effect of the implemented intervention measures, which have contributed to reductions in operational energy demand, and also demonstrate the potential for further energy savings through the wider application of the simulated measures.

7.2. Carbon emissions

The twelve studied measures presented in **6 Energy- and carbon-saving interventions**, lead to reductions in carbon emissions, either through reductions in energy consumption, or the integration of renewable based energy vectors.

Interventions grouped as reduced operational modes and sufficiency measures show reductions of up to 7% of the total carbon emissions, without requiring any energetic or financial investment. These measures only require adapting the operation of technical installations. Renovations lead to potential savings of up to 27%, however they require financial investments, and it takes between 1 and 21 years to compensate for the embodied carbon equivalent emissions.

The integration of renewables shows the potential for savings of up to 90% of carbon emissions. The analysed photovoltaic installations save between 12% and 14% of carbon emissions and take up to 6 years to compensate for the added embodied carbon equivalent emissions, but the scenarios change for different production capacities.

The carbon savings from the use of hydrogenated vegetable oil in the existing boilers of Building D, refer to its carbon content. It varies according to the feedstock used in the production. Facility managers must define a procurement procedure to ensure the quality of the fuel, and the expected impact.

As per the use of hydrogen in the combined heat and power engines of the district heating network, the investment decision and the choice of fuel is only lying in the energy supplier, and the building manager has no decision-making authority in this regard. Nevertheless, certificates of carbon emissions should be required to ensure the impact in the carbon emission.

The comparison of intervention measures on carbon emissions confirms the essential role of renewable energy, which delivers the greatest reductions. Nevertheless, reduced operational modes, sufficiency strategies, and renovation measures remain vital energy efficiency approaches. The implementation of these measures has been demonstrated to enhance the overall performance of the building, enabling the redirection of renewable energy towards other demands and maximising its contribution to decarbonisation.

7.3. Economic

The economic assessment is structured by groups of intervention measures. The first and second groups, which include reduced operational modes and sufficiency strategies focus on adapting the operation of existing technical installations to actual needs. As a result, they do not require investments, and only generate energy savings and reduced energy bills, leading directly to positive cash flows.

The third group concerns renovation measures, which require significant financial investment. However, a portion of the associated costs relates to standard maintenance, necessary to preserve building functionality. In this analysis, only the investment portion is considered, yet even then, payback times exceeding 25 years are observed. This highlights the challenge building managers face when deciding on measures to improve the thermal resistance of existing buildings, particularly when the long-term use of the building is uncertain.

Among specific measures considered, the installation of window blinds represents a relatively small investment (under €100,000) with a payback time of 27 years. Insulating radiator niches and, repairing and insulating windows still represent relatively low investments, of €200,000 to €300,000, respectively. Payback times also increases to 44 years for the windows and 142 years in the case of the radiator niches.

Larger interventions, such as window replacement and roof insulation, involve investments ranging from €1,000,000 to €2,000,000, with payback times of 40 and 38 years. These high costs and payback timers create substantial barriers to implementation, particularly in budget-constrained contexts.

The integration of renewable energy shows a wide variation in economic feasibility. Photovoltaic systems, for instance, require moderate investments between €150,000 and €250,000, depending on system size, but these costs are recovered within 4 years. By contrast, replacing heating oil with hydrogenated vegetable oil in boilers requires only a minimal investment (under €1,000), but leads to higher operating costs, of almost €90,000 per year, due to the higher price of low-carbon fuels. Similarly, converting a cogeneration heat and power plant from natural gas to hydrogen requires investment at the energy provider level. For building managers, the impact is reflected only in higher energy bills, with additional annual costs estimated between €100,000 and €150,000 in the scenarios analysed. In the longer term, these conditions are expected to improve through large-scale deployment, cost reductions, and the parallel development of the necessary infrastructure, driven by policy support.

In summary, the economic analysis demonstrates the complexity of comparing investment levels, payback times, and operational impacts across different intervention measures. While operational adjustments and some renewable solutions provide clear financial benefits, renovation measures often entail long payback periods and high upfront costs, creating substantial barriers for decision-makers. This underlines the importance of integrated evaluation methods that account not only for financial feasibility but also for long-term carbon reduction and sustainability goals.

7.4. Comfort

During the months of February and March 2025, comfort surveys were distributed to 92 students in two auditoriums, and two classrooms (Reference room and Pilot room), in Building B. At the same time, physical comfort parameters were monitored, following the methodology presented in **3.3.5 Comfort parameters**. As described in **3.6.4 Comfort assessment** this data allows us to calculate and estimate the physical and perceived predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) persons, as presented in **Table 7.2**.

No pattern is observed in the results presented in **Table 7.2**, neither between the rooms, nor in the same room over different days. No correlation between physical measured parameters and perceived comfort can be established. However, it is possible to observe both from the physical measurements and in terms of perceived comfort that all rooms, in all measuring days are between slightly cold and slightly warm, and most of the cases are close to neutral.

Table 7.2: PMV and PPD calculations and based on measured physical parameters and perceived comfort surveys in winter 2024-2025 at Building B

Winter 2024-2025 Building B	Audit A	Audit C	Reference			Pilot		
	26/Feb	11/Mar	11/Mar	13/Mar	14/Mar	10/Mar	12/Mar	14/Mar
Radiant temperature [°C]	20.1	22.2	20.0	21.4	20.8	21.6	22.7	21.6
Air temperature [°C]	20.2	22.4	20.1	21.4	21.6	21.9	22.7	21.7
Air velocity [m/s]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2
Relative Humidity [%]	38.7	44.4	47.0	38.6	37.5	33.2	42.5	30.8
Clothing – mean [clo]	1.2	1.5	0.9	1.4	1.4	1.0	0.8	1.6
Metabolic activity [met]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
PMV – mean (Physical)	**-0.57**	**0.32**	**-1.09**	**-0.01**	**-0.06**	**-0.53**	**-0.56**	**0.08**
PPD (Physical)	11.7%	7.3%	30.0%	5.0%	5.1%	10.8%	11.7%	5.1%
PMV (Perceived – Group 2)	**0.00**	**0.00**	**0.50**	**0.00**	**0.00**	**1.00**	**0.00**	**0.50**
PPD (Perceived PMV – Group 2)	5%	5%	10%	5%	5%	26%	5%	10%

The analysis of the physical measurements on 11/03/2025 from Reference room, leads to a predicted percentage of dissatisfaction of 30%, nevertheless based on the perceive comfort survey, this percentage reduces to 10%. The results from the perceived comfort questionnaires also show that 33% of the people rated the indoor climate as neutral, and the other 66% indicated it as overall good.

With regards to the Pilot room, 27% of the people were between slightly dissatisfied and dissatisfied, in the perceived comfort survey on 10/03/2025, while 40% of them rate the indoor climate as slightly bad. Meanwhile, the analysis of the physical measurements shows only 10.8% of predicted percentage of dissatisfaction (PPD).

The comparison of the calculated mean PMV value for Reference and the Pilot rooms, over the three days of physical measurements and the perceived comfort survey data collection, shows a small difference, between -3% and 7%, with regards to the full range. The first one refers to the physical measurements, where Pilot room is rated as -0.3, which is slightly colder than Reference room, with -0.1. Conversely, the PMV obtained from the perceived comfort surveys show a PMV of 0.5 for the Pilot room, while the Reference room has a neutral PMV of 0. Considering the small differences, and all the values close to neutral indoor climate, it is inferred that comfort is not affected with the renovations.

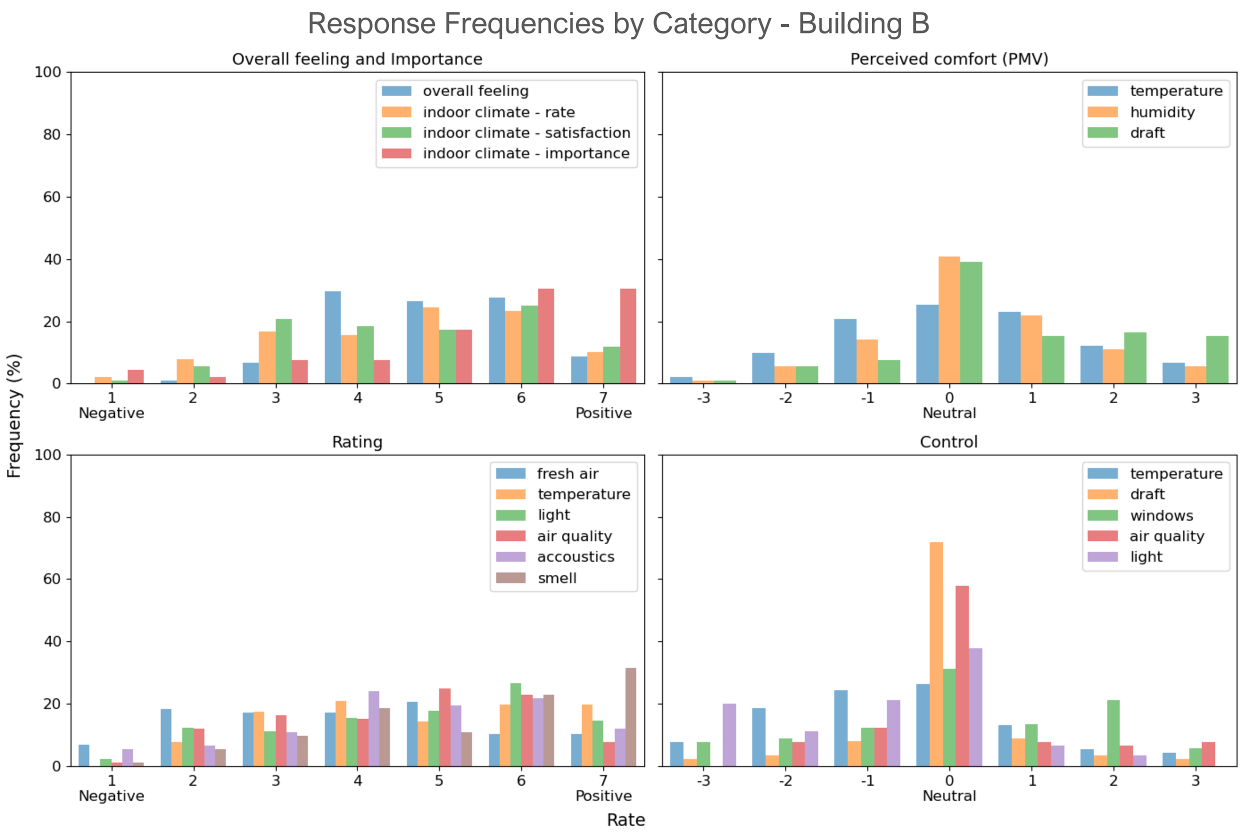

Figure 7.3: Combined results of all perceived comfort questionnaires, applied during winter, at Building B

In terms of the perceived comfort **Figure 7.3** shows the combined results for all surveys. The questions were distributed in groups as described in **3.6.4 Comfort assessment**. The top left plot shows that 83% of the people were feeling between neutral and good during the surveys, and thus, no negative impact in the perceived comfort is expected in this sample. The indoor climate is rated between slightly important to very important for 77% of the people, and in general the indoor climate rate and the level of satisfaction follow similar distributions. The perceived comfort parameters directly related to the predicted mean vote (PMV) display a normal distribution, with the highest frequencies located around neutral, as already discussed. The rating of the different parameters is nearly equally distributed between bad and good for all six parameters, but in general a slight increase is observed towards the positive rates. A more representative result is obtained when analysing the campaigns separately.

Finally, with regards to the willingness to control the parameters, draft and air quality does not seem to require changes, although 21% of the people would like to open the windows. In terms of temperature and light 50% of the people would like to make the rooms warmer and brighter. In the analysed classrooms both the light and the windows are manually controlled. The radiators are the only devices that are centrally controlled. In the Pilot room the radiator valves were replaced by manual versions, to explore the impact of the control on perceived comfort, but no difference is observed.

7.5. Performance assessment outcomes

Building on the stakeholder engagement (Step 1), the technical and behavioural insights gained through the energy audit (Step 2), and the definition of potential interventions (Step 3), Step 4 addresses the performance assessment, allowing the comparison between interventions. In this stage, an integrated performance indicator becomes a key consideration for decision-making stakeholders, as already emphasised in **4 Behavioural approach**, and could not be neglected when comparing measures.

The first two sets of interventions analysed in this study, called reduced operational modes and sufficiency, do not require investments. Therefore, the reductions in energy consumption directly led to up to 7% reductions in the yearly energy bills.

The renovations hardly represent an interesting investment, with high payback times, even when associated with yearly carbon emission savings of up to 27%. However, the main motivation for implementation relates to reducing the impacts in climate change, while ensuring comfortable conditions for users.

The integration of photovoltaic panels on the roofs of educational buildings contributes to a reduction in both carbon emissions from electricity consumption and associated energy bills. The payback time of this investment depends on the capacity of the system, and a thorough installation. In the two analysed cases in 4 years the investment is recovered. Conversely, replacing the energy vector requires no significant upfront investment for the building manager, although it can result in higher operational costs under current fuel price conditions.

"Radiator niche" and "Window repair and insulation" were excluded from the chart, since their primary embodied carbon equivalent emissions are not compensated within the analysed period

Figure 7.4: Avoided carbon cost of the analysed intervention measures, considering 10 years of the building operation

To enable a comparison between the different intervention measures, the avoided carbon cost over ten years of operation is calculated using **Equation 3.14**, and summarized in **Table 7.1**. The results are plotted in **Figure 7.4** to compare the performance of the measures. They demonstrate a positive impact for reduced operational mode and sufficiency measures, as these require no investment, while delivering carbon emission reductions and lowering operational costs. The exception is the addition of sun blinds, to be closed during the night, to reduce thermal losses through the windows. In this case, even when only accounting for the cost of installing new blinds on the 132 windows currently without them, and treating the remaining expense as maintenance, still represents the highest avoided carbon cost.

Although the installation of photovoltaic panels requires an initial investment, it provides both a positive economic return and significant carbon emission reductions, even after accounting for the embodied carbon from panel production. Among the measures analysed, it achieves the most favourable avoided carbon costs.

Furthermore, the results indicate that, over the 10-year time frame considered in this analysis, the integration of renewable energy systems outperforms renovation measures in terms of avoided carbon cost.

Considering the reduction in carbon emissions, the 32% higher fuel cost associated with replacing heating oil with hydrogenated vegetable oil corresponds to an avoided carbon cost of -0.10 €/kgCO_2 for the high-savings scenario and -0.19 €/kgCO_2 for the low-savings scenario.

The adoption of hydrogen in combined heat and power engines connected to a district heating network is analysed here by considering an increase in the final thermal energy cost. Using **Equation 3.14**, for Building B, and considering a 0.15 €/kWh higher operating cost for hydrogen, the avoided carbon cost is calculated between -0.41 €/kgCO_2 and -0.73 €/kgCO_2 for low and high emission scenarios, respectively.

In the case of hydrogen, a reduction in the energy vector cost is required to prevent additional costs over an indefinite period. Hydrogen auctions organised by the European Hydrogen Bank in 2024 and 2025 aim to close the price gap between fossil and renewable hydrogen while supporting the scaling up of electrolysis deployment by offering a premium price [62]. Selected projects applied for premium rates between 0.20 €/kgH_2 and 0.60 €/kgH_2, which is over 85% lower than the 4 €/kgH_2 cap offered in the latest edition [63]. This indicates that, with adequate support, renewable hydrogen is expected to become competitive with fossil fuels in the coming years.

Figure 7.4 shows that, among renovation measures, the lowest avoided carbon cost is achieved by the inverted roof with an added 240 mm insulation layer. In contrast, improvements such as radiator niche insulation and window repair or insulation do not compensate their primary carbon emissions within the analysed period. The highest avoided carbon cost is associated with full window replacement, primarily due to the long carbon compensation time needed for the embodied energy of the materials.

No negative impacts on indoor comfort were observed for the analysed measures, reinforcing their suitability for implementation in educational buildings. Behavioural and operational changes achieved measurable reductions without compromising user well-being, while the integration of renewable energy systems does not affect building users. Renovation measures further supported energy and carbon savings while maintaining adequate thermal conditions. Even in cases where payback times are long or avoided carbon costs are high, preserving comfort remains a critical parameter, as it is fundamental to the primary function of educational buildings.

Overall, the comparison of interventions highlights that no single measure can be regarded as universally optimal, but rather that their effectiveness depends on balancing energetic, carbon, economic, and comfort-related aspects. Behavioural approaches and reduced operational modes emerge as immediate and cost-free strategies with measurable benefits, while photovoltaic integration demonstrates strong long-term potential by combining economic returns with substantial carbon savings. The replacement of heating oil with hydrogenated vegetable oil, implemented with due diligence, constitutes a straightforward and immediate solution to reduce carbon emissions. Nevertheless, the elevated operational expenses remain a challenge. In contrast, renovation measures, though important for improving comfort and reducing demand, often show limited economic attractiveness within the considered timeframe due to high embodied emissions and long payback periods. Finally, the future competitiveness of renewable hydrogen remains closely tied to policy support and market developments. Together, these findings emphasise the importance of a holistic perspective in decision-making, where cost efficiency, carbon reduction, and user well-being are jointly assessed to design robust pathways for decarbonisation.

8. General Conclusions and outlook

This study introduces a comprehensive framework for reducing energy consumption and carbon emissions in educational buildings. The proposed framework is centred on four interconnected steps: a behavioural approach for the engagement of stakeholders, energy auditing, the identification of interventions, and performance assessment. A key contribution lies in the definition of an integrated performance indicator, the avoided carbon cost, which enables systematic comparison of interventions and provides a reference for decision-making processes. The framework and results demonstrate how combined technical and behavioural interventions can be identified, implemented, assessed, and improved in practice.

Grounded in the well-documented energy performance gap, the framework emphasises the potential contribution of existing buildings to reduce carbon emissions in the building sector. The methodology has been implemented in the context of educational buildings in Luxembourg that were constructed prior to 1990 and the initial energy efficiency standards, where the implementation of interventions is hindered by the uncertainty regarding their long-term use. In this context, the framework provides a replicable methodology for defining and implementing energy- and carbon-saving measures that are tailored to the characteristics of such buildings, while ensuring user comfort.

Step 1 – Behavioural Approach

The behavioural approach focused on engaging stakeholders, including building users and managers, to understand their attitudes, motivations, and perceived barriers toward energy-saving behaviours. Surveys and interviews revealed a generally positive disposition: approximately 70% of participants recognised the value of pro-environmental actions, while around 60% reported intentions to modify their behaviour. However, limitations were observed in perceived control, access to resources, and the presence of incentives or clear sustainability indicators. Building managers, in particular, identified budget constraints and unclear institutional sustainability indicators as key barriers to implementing interventions. These findings emphasised the need for interventions that are both realistic and supported by stakeholders, and for the development of clear performance indicators to guide decision-making and prioritisation. Step 1 thus provided a crucial foundation for identifying practical and acceptable energy-saving opportunities, while highlighting the organisational and financial factors that must be addressed to enable effective implementation.

Step 2 – Energy Audit

The energy audit provided a detailed assessment of the energy performance of the analysed buildings, quantifying electricity and thermal consumption and comparing it against local benchmarks. Analyses revealed significant opportunities for operational optimisation, particularly in the electrical systems, where high baseload consumption and misaligned schedules were observed. The audit also identified major energy consumers within each building, such as lighting, digital consumers, or specialised equipment. Thermal losses were primarily associated with low-performing windows and insufficient insulation on the roof and façade. Step 2 built directly on the behavioural insights from Step 1, by involving stakeholders and translating user patterns and occupancy data into a clear picture of technical performance, highlighting where interventions could achieve high impact with minimal investment and minimal disruption to comfort.

Step 3 – Energy- and carbon-savings Interventions

Step 3 combined the findings from behavioural engagement and technical diagnostics to define a structured portfolio of interventions. Measures were categorised into (1) reduced operational modes, (2) sufficiency measures, (3) renovations, and (4) renewable energy integration. The first two categories focus on optimising operational settings and require no investment, including actions such as adjusting equipment schedules, limiting unnecessary baseload consumption, and aligning technical systems with actual occupancy patterns. These measures provide immediate energy and carbon savings while maintaining user comfort.

The case studies demonstrate the effectiveness of combining reduced operational modes, sufficiency measures, and targeted renovations in achieving substantial energy and carbon savings. In Building C, measures such as adjusting operational schedules and temporarily closing the swimming pool generated savings of 32 MWh/a of electricity and 128 MWh/a of heat, corresponding to a 10% reduction in carbon emissions. In Building B, the integrated application of reduced heating during holidays, optimised use of blinds, ventilation and lighting sufficiency, and roof insulation yielded even greater savings of 64 MWh/a of electricity and 407 MWh/a of heat, translating into a 32% reduction in carbon emissions. Together, these results highlight the strong potential of a combined approach, where operational adjustments, behavioural sufficiency, and selected renovation measures work synergistically to deliver significant and measurable reductions in energy use and carbon emissions.

Renovation measures, such as improving insulation, require careful consideration of energy, carbon emissions, and financial investment over the analysed period, with a focus on maximising efficiency and ensuring the effective use of resources. The inverted roof and window replacement showed potential to reduce carbon emissions by 19% and 27%, respectively.

Finally, the integration of renewable energy systems, such as photovoltaic panels and low-carbon fuels like hydrogenated vegetable oil (HVO) or hydrogen, has the potential to deliver substantial carbon emission reductions, up to 90% compared with the reference year (2018), while accounting for embodied carbon emissions. These results are made possible through careful verification and the use of certificates of origin, ensuring the credibility of the reported savings. In the case of HVO and hydrogen, operational costs are currently higher, although they are expected to decrease in the coming years due to ongoing political support, market development, and evolving regulations. The replacement of heating oil with HVO allows for a rapid reduction in carbon emissions, while the use of hydrogen in cogeneration engines for district heating depends on the energy supplier and the gradual development of local infrastructure.

By combining operational optimisation, targeted renovations, and renewable energy integration, Step 3 ensures that energy consumption is minimised, resources are efficiently used, and renewable energy is leveraged effectively. The step translates the diagnostic insights from Steps 1 and 2 into a tangible, actionable plan, aiming to prioritise interventions that achieve the greatest impact while remaining realistic, cost-effective, and aligned with stakeholder acceptance.

Step 4 – Performance Assessment

In Step 4, building on the insights from stakeholder engagement (Step 1), the energy audit (Step 2), and the definition of interventions (Step 3), the effectiveness of the proposed measures was quantified using the integrated performance indicator: the avoided carbon cost (ACC). This indicator represents the cost of each measure in euros per kilogram of CO_2 avoided, calculated by relating the net operational savings (after deducting investment) to the effective carbon reductions achieved once embodied emissions have been compensated, over the analysed period. In this way, the ACC enables direct comparison across measures and supports informed decision-making.

Operational measures, including reduced operational modes and sufficiency strategies, delivered immediate benefits, leading to reductions of up to 10% in electricity consumption, 12% in heating demand, and 22% in carbon emissions across the analysed buildings. Renovation measures together, demonstrated the potential, to reduce heat consumption and carbon emissions by almost 50%. However, they require energetic and financial investment and typically give long payback times. In terms of embodied carbon equivalent emissions, certain measures, such as radiator niche insulation and window repair, presented compensation times longer than the 10-year operational period adopted in this analysis.

Regarding renewable energy integration, photovoltaic systems provided up to 14% reduction in carbon emissions, while low-carbon fuels such as hydrogenated vegetable oil in heating boilers, and hydrogen in cogeneration engines, showed a wider range of impacts, with potential reductions of up to 86% and 90% respectively, depending on feedstock, production processes, and operational scenarios. Current operational costs remain higher. Although recent hydrogen valley projects show a downward trend in prices, most remain in the range of 4–6 €/kgH_2. The feasibility analysis indicates, however, that hydrogen would need to be priced below 1.5 €/kgH_2 to compete with current natural gas costs, and 1.6 €/kgH_2 when considering current carbon taxes, underscoring that achieving cost-competitive deployment remains a major challenge.

The avoided carbon cost distribution across the analysed measures highlights clear differences in effectiveness between intervention categories. Photovoltaic systems stand out as the best-performing option overall, with an avoided carbon cost of 1.31 €/kgCO_2. Reduced operational modes and sufficiency measures also show strong performance, yielding negative avoided carbon costs between 0.78 and 0.95 €/kgCO_2. These approaches not only reduce emissions but also lower energy bills, making them highly cost-effective, and in the case of operational interventions, immediately actionable.

In contrast, renovation measures such as roof insulation (-2.68 €/kgCO_2) and window replacement (-5.11 €/kgCO_2) show higher avoided carbon costs, as their investment is not fully compensated within the 10-year analysis period. Even less favourable are radiator niche insulation and window repairs, where embodied carbon equivalent emissions could not be compensated during the timeframe. Low-carbon fuels occupy an intermediate position: hydrogenated vegetable oil shows avoided carbon costs of -0.10 to -0.19 €/kgCO_2, while hydrogen-based solutions range from -0.41 to -0.73 €/kgCO_2, both more competitive than renovation measures. The least cost-effective intervention is the addition of external sun blinds, to reduce heat losses overnight, reaching -7.90 €/kgCO_2 due to their relatively high embodied energy and limited operational savings.

Overall, the analysis confirms that photovoltaic systems deliver the best performance, of the tested approaches, while operational and sufficiency strategies provide immediate, low-cost benefits. Renovation and fuel-switching measures remain less competitive in the short term but could gain viability under longer horizons or with stronger market support.

Across the analysed interventions, no negative impacts on indoor comfort were observed. Behavioural and operational measures achieved measurable energy and carbon reductions without affecting users, while renovation and renewable energy measures further supported savings with no impact in thermal conditions. Step 4 thus validated the overall framework, demonstrating that integrating behavioural engagement with detailed technical analysis enables durable and measurable reductions in energy consumption and carbon emissions. This is achieved by balancing technical and operational constraints, while providing an integrated indicator to compare different intervention measures, and support the decision-making process.

Furthermore, the analysis of historical energy consumption over the past years shows that, at the educational buildings, electricity use was reduced by up to 30% compared to the reference year (2018), while normalised heat consumption decreased by up to 22%, in the case of Building B. These results underline the significant impact of direct stakeholder engagement, demonstrating that active involvement of building users and managers can drive meaningful and sustained reductions in energy demand.

Conclusion

The application of the proposed framework demonstrates that combining behavioural and technical approaches offers a robust pathway to reducing energy consumption and carbon emissions in educational buildings. By integrating behavioural approach, detailed energy auditing, targeted intervention planning, and performance assessment, the framework ensures that measures are both technically effective and socially acceptable. Immediate, low-cost interventions, such as optimising operational schedules and reducing unnecessary baseload, provide tangible benefits without compromising user comfort. Renovation and renewable energy strategies also contribute to carbon savings during operation, but their implementation requires careful attention to avoid false impacts caused by the performance gap, and proper verification of emission certificates. In this context, it is important to recognise that replacing existing buildings typically requires around twenty years to compensate for the embodied energy of new construction, reinforcing the value of prioritising operational improvements and incremental upgrades whenever possible.

The use of an integrated performance indicator, the avoided carbon cost, proved essential in quantifying and comparing the impact of different measures, supporting informed decision-making across complex stakeholder networks. Beyond the specific case of pre-1990 educational buildings in Luxembourg, the study highlights the potential for replication in similar contexts, demonstrating that practical, cost-effective interventions can overcome common barriers such as limited budgets, operational inertia, and uncertainty regarding long-term building use. Moreover, even when the energy performance gap is properly accounted for, deep renovations are often constrained by the need for significant upfront investments. Adopting a strategy of pinpointed renovations can help overcome these barriers by enabling smaller, more manageable interventions that remain compatible with long-term improvement pathways.

Ultimately, this work underscores the value of a structured, stepwise approach in bridging the gap between awareness and action. By aligning behavioural engagement, technical diagnostics, and performance-based evaluation, the framework provides a coherent methodology for achieving measurable, sustainable reductions in energy consumption and carbon emissions, contributing to the broader goals of the energy transition and climate mitigation.

Challenges, Limitations and Outlook

Despite the promising outcomes, several challenges were encountered in applying the proposed framework. Aligning behavioural engagement with technical interventions requires sustained coordination among diverse stakeholders, including building managers, users, and institutional decision-makers. Implementation is often impacted by operational inertia, limited resources, and heterogeneous occupancy patterns, which complicate the adoption of optimised schedules and efficiency measures, where the integration of automation solutions is not straightforward. Data collection from outdated systems further adds complexity, often requiring local verification to ensure reliability. Additionally, the feasibility of deploying low-carbon technologies, such as hydrogenated vegetable oil or hydrogen, remains highly dependent on market dynamics, feedstock availability, and evolving regulations. Addressing these challenges demands clear communication, thorough planning, and continuous monitoring to secure both effectiveness and acceptance.

This study also has inherent limitations. Data availability and quality, particularly in relation to occupancy and detailed sub-metering, restricted the granularity of several analyses. The thermal assessment relied on local measurements, extrapolations to the entire building, and stationary thermal models, progressively refined through repeated analysis cycles. The evaluation of renewable energy integration, embodied carbon, and long-term financial impacts necessarily relied on assumptions that may vary across contexts and over time. Furthermore, the behavioural surveys captured intentions and perceptions, but did not guarantee long-term adherence to energy-saving practices, which requires constant reminder and training. These constraints must be considered when interpreting the results or transferring the methodology to other settings, but they also represent opportunities for future research.

Future investigations should extend measuring and monitoring strategies, enabling timely detection of deviations in consumption patterns and supporting the refinement of the framework, by integrating transient modelling approaches, in specific critical analysis. This study addressed the impact of involving building users and operational staff in achieving savings through participatory engagement, which enhances acceptance and perceived comfort. However, realising further results requires continuous reminders and training to sustain and deepen this involvement. In renovation scenarios, the use of alternative materials with lower embodied carbon should be explored, particularly for targeted, low-investment interventions that can help overcome budgetary barriers. Finally, emerging low-carbon technologies, such as hydrogen-based systems and advanced photovoltaics, warrant further evaluation to assess their technical feasibility, cost-effectiveness, and environmental benefits in educational and other public buildings.

Recommendations

Operational and Behavioural Measures

- Prioritise low-cost, high-impact interventions, such as optimising equipment schedules, reducing baseloads during unoccupied periods, and avoiding oversized ventilation or lighting operations.
- Maintain continuous engagement with users and managers to ensure behavioural measures are understood, accepted, and applied. Clear communication and straightforward guidance materials can reinforce adherence.

Technical Renovation and Renewable Integration

- Focus energy-efficiency upgrades on components with the highest losses, such as windows, envelope elements, and outdated ventilation or lighting systems, prioritising materials with low embodied energy to maximise avoided carbon cost.
- Integrate renewable energy systems, including photovoltaics and low-carbon heating solutions, in line with long-term energy and carbon objectives, while accounting for embodied energy, operational costs, and support availability.

Performance Monitoring and Decision Support

- Employ integrated performance indicators, such as avoided carbon cost, to evaluate and compare interventions, thereby guiding prioritisation and resource allocation.
- Establish systematic monitoring and verification protocols to assess the effectiveness of measures, identify deviations, and support continuous improvement.

Policy and Organisational Alignment

- Encourage institutional policies that promote energy-saving behaviours and investments beyond deep renovation and electrification measures, supported by training, incentives, and transparent sustainability indicators.
- Facilitate replication of the framework in other educational and public buildings through dissemination of methodological guidance, stakeholder engagement strategies, and performance evaluation criteria.

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Annex

Annex I - User pro-environmental behaviour questionnaire

The questionnaire is composed by two parts. The first with 8 statements, assessing pro-environmental behaviours, and the second containing 5 statements, focused on the barriers faced to engage in such behaviours. The answer to these statements follows a scale from 1 to 7, where 1 corresponds to strongly disagree and 7 to strongly agree.

Pro environmental behaviours (PEBs)

1. For me, to engage in PEBs that aim to reduce energy consumption of the school/university building is valuable.
2. For me, to engage in PEBs that aim to reduce energy consumption of the school/university building is beneficial.
3. The decision to engage in PEBs that aim to reduce energy consumption of the school university building is under my control.
4. I have enough opportunities, time, and resources to engage in PEBs that aim to reduce energy consumption of the school/university building
5. I change my daily lifestyle to better the environment.
6. In general, I have the intention to engage in PEBs that aim to reduce energy consumption.
7. In general, people I admire think that I should perform PEBs that aim to reduce energy consumption on a regular basis during the next year.
8. People who are important to me will themselves perform PEBs that aim to reduce energy consumption on a regular basis during the next year.

Barriers to engage in pro-environmental behaviours regarding energy consumption

9. I know which behaviours can reduce energy consumption and are therefore good for the environment (pro-environmental).
10. Reducing energy consumption is an important topic to me
11. I see my classmates engage in behaviours that aim to reduce energy consumption of the school/university building.
12. It is inconvenient to engage in PEBs that aim to reduce energy consumption of the school/university building

13. I get rewarded when I engage in PEBs that aim to reduce energy consumption of the school/university building.

To allow further classification, the participants were asked about their age and gender.

Annex II - Barriers for implementing sustainable interventions

1. What are your work responsibilities (make suggestions, identify solutions, technically or financially evaluate them, decision making) regarding the implementation of new sustainability interventions?
2. Where is sustainability/PEB in the priorities of your personal opinion and of your work/company?
3. What are the barriers (responsibility, priorities, budget, technical) that you encounter at work which would prevent the implementation of new sustainability interventions?
4. Does the company where you work include any parameter for promoting sustainable interventions, or does it include sustainability as a parameter for decision making?

Annex III - Local electricity consumption measurements

Fixed electricity meters

Within the ENERGE Project, the NG-9 Next Generation Power Analyzer from Energy Team was installed at three educational buildings in Luxembourg, including buildings A, C and D. This electrical meter has 9 current sensors that can measure from 1 to 2000 amps, allowing different measuring configurations. In the case of the ENERGE Project, it was used to measure different parts of the building. The devices are associated with a Sigfox metering transmitter which sends the data to a central platform, where the information is stored.

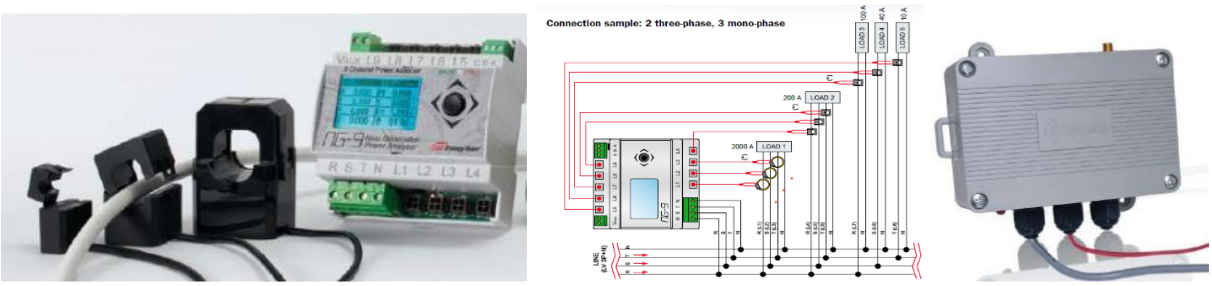


Figure A.1: (a) Electrical meter; (b) Setup example; (c) Associated Sigfox transmitter

The current measurement is carried out by a current clamp sensor that snaps around the electrical wires. The type of sensor is chosen according to the intensity of the current to be measured:

- Rogowski coil from 100 to 2000 A (consumption of the entire school).
- Standard size current clamp from 20 to 200 A (consumption of the entire building).
- Miniature size current clamp from 10 to 100 A (a floor or a classroom).
- Mini-transformer with output voltage.

Mobile Electricity Meters

The energy consumption of specific parts of the buildings or technical installations is also possible using mobile electrical meters, such as the Fluke 435 Power Quality Analyzer. This meter follows the same principle as the fixed one. It measures the current of a determined installation by placing clamps around the cables to be measured. This information is recorded by the energy meter and combined with the measurement of the voltage, provides the energy consumption within the measured period.

This device provides flexibility, allowing one to measure different parts of the building and different technical installations, for a characteristic period that provides references to identify the distribution of the overall consumption.

Figure A.2: (a) Electrical meter; (b) Current clamps

Annex IV - Thermal transmittance analysis

Theoretical method

From the thermal conductivity of a material and its thickness, the thermal resistance of a component can be determined. The thermal resistance of the component is composed of the sum of the thermal resistance of each one of the layers composing it, as presented in **Equation A.1** and **Equation A.2**. As shown in **Equation A.3**, the thermal transmittance also includes the internal and external thermal surface resistances regarding the convection effects mainly driven by the wind speed and the thermal radiation related to the emissivity of the material and the temperatures. The internal and external thermal surface resistances are standardised in ISO 6946:2017 [141], for a general condition of the surface against the air, an internal and external surface temperature of 20°C and 0°C respectively, emissivity of 0,9, and external wind speed of 4 m/s. Considering a horizontal heat flow, the internal and external thermal surface resistance values adopted in this analysis are R_{si} = 0,13 m^2K/W and R_{se} = 0,04 m^2K/W.

Equation A.1: Thermal resistance of each layer of the building component

$$R_n = \frac{d}{\lambda} \left[\frac{m^2K}{W}\right] \tag{A.1}$$

where:

R_n thermal resistance of each layer of the building component [m^2K/W]
d thickness of the layer [m]
λ thermal conductivity [W/m/K]

Equation A.2: Thermal resistance of the building component

$$R_{component} = R_1 + \ldots + R_{n-1} + R_n \left[\frac{m^2K}{W}\right] \tag{A.2}$$

where:

$R_{component}$ thermal resistance of the building component [m^2K/W]
R_n thermal resistance of each layer of the building component [m^2K/W]

Equation A.3: Thermal transmittance

$$U = \frac{1}{R_{si} + R_{component} + R_{se}} \left[\frac{W}{m^2K}\right] \quad \text{(A.3)}$$

where:

U	thermal transmittance of the building [W/m^{2}K]
R_{si}	internal thermal surface resistance [m^{2}K/W]
$R_{component}$	thermal resistance of the building component [m^{2}K/W]
R_{se}	external thermal surface resistance [m^{2}K/W]

Although this method has great advantages, such as being a simple calculation, it carries high uncertainties related to unknown stratigraphy and thermophysical properties, especially characteristic for older buildings with limited documentation [142].

Heat flow meter

The heat flow meter test is used to determine the thermal transmittance of building components by measuring the heat transfer rate through the specific component, and the inside and outside, air and surface temperatures. It is established based on the assumption that in a state of equilibrium a heat flow density flows from through a component submitted to a temperature gradient between internal and external conditions. It provides valuable data for the analysis of the overall thermal resistance of the façade and related transmission heat losses.

As shown in **Figure A.3**, the heat flow meter plate is installed at the internal wall, together with one temperature sensor in contact with the internal surface of the component and one temperature sensor measuring the internal air temperature a few centimetres away from the internal surface of the component. At the outside of the wall façade, two more temperature sensors are installed, following the same configuration as the internal ones. The first sensor is installed on the external wall surface, whereas the second one measures the outside air temperature, placed a few centimetres away from the external surface of the component. All these sensors are then connected to the datalogger, and measurements are done for at least 72 hours, to avoid the interference of the thermal inertia of the component in the measurements. Furthermore, the test is to be realised over periods when there is an important temperature gradient between inside and outside, to ensure significant heat flows. Finally, the experiment must be set up at a location which avoids external interferences, such as windows, radiators, or discontinuities at the surface.

The digital heat flow board is equipped with a sensitive sensor enabling the measurement of heat flow densities. It uses an analog-to-digital converter to measure the output voltage of the heat flow plate. The temperature sensors are thermocouples NiCr-Ni thermo wire. In this sensor two wires have different thermal expansions and induce different stress based on the temperature. This stress values are converted into a temperature by the data logger.

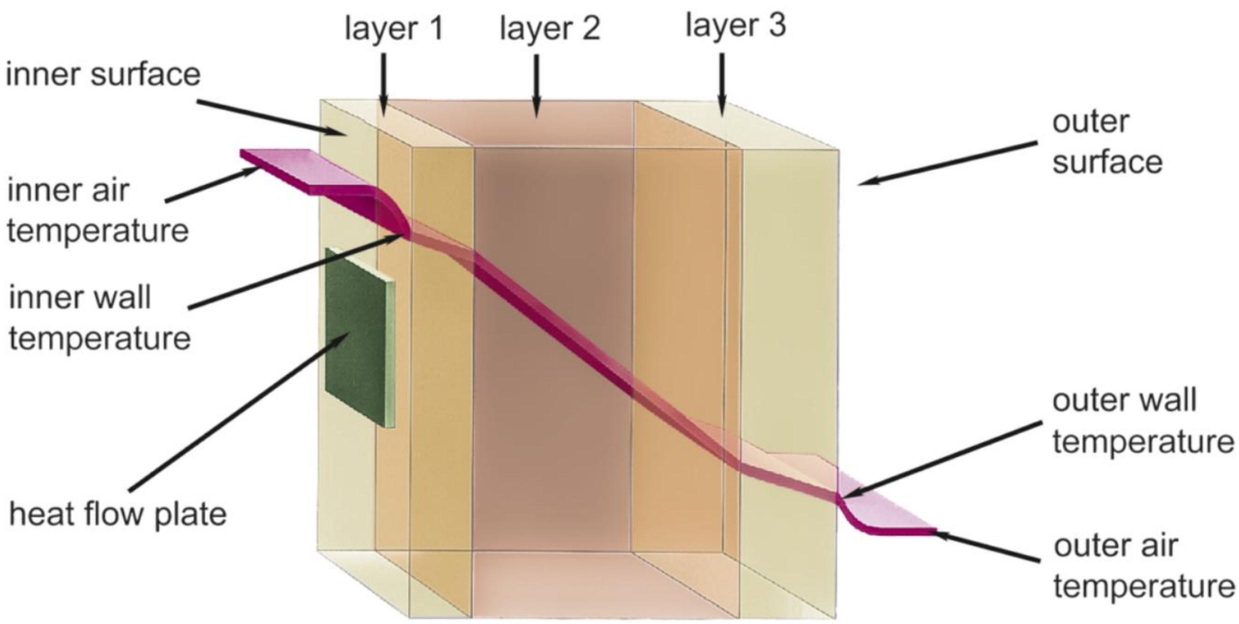


Figure A.3: Measurement principle [143]

Table A.1: Ahlborn measured parameters, range, accuracy and resolution for the heat flow meter experiment to determine measure thermal transmittance [144]

Parameter	Range	Resolution	Accuracy
Heat flow plate [Wm]	(-2000)-2000 Wm	0.1 W/m^2	5%
Temperature [°C]	(-200)-1370 °C	0.01 K	± 0.2 K ± 0.02%

From the collected data it is possible to calculate the thermal resistance of the component, and the internal and external surface thermal resistances, as shown in **Equation A.4**, **Equation A.5**, **Equation A.6** and **Equation A.7**.

Equation A.4: Heat flow expression

$$\dot{q} = U_c \times (T_i - T_e) = \frac{1}{R_{si}} \times (T_i - T_{si}) = \frac{1}{R_{se}} \times (T_{se} - T_e) = \frac{1}{(R_1 + \cdots + R_n)} \times (T_{si} - T_{se}) \quad \text{(A.4)}$$

where:

$\dot{q}$	heat flow [W/m^2]
U_c	thermal transmittance of the building component [W/m^{2}K]
R_{si}	internal thermal surface resistance [m^{2}K/W]
R_{se}	external thermal surface resistance [m^{2}K/W]
R_n	thermal resistance of each layer of the building component [m^{2}K/W]
T_i	internal air temperature [°C]
T_e	external air temperature [°C]
T_{si}	internal surface temperature [°C]
T_{se}	external surface temperature [°C]

Equation A.5: Average method to calculate the thermal resistance of the building component with internal and external thermal resistances [145]

$$R_{component} = \frac{\sum_{j=1}^{n}(T_{sij} - T_{sej})}{\sum_{j=1}^{n} q_i} \left[\frac{m^2K}{W}\right] \quad \text{(A.5)}$$

where:

$R_{component}$	thermal resistance of the building component with internal and external thermal resistances [m^{2}K/W]
q_i	heat flow [W/m^2]
T_{sij}	internal surface temperature [°C]
T_{sej}	external surface temperature [°C]

Equation A.6: Average method to calculate the internal thermal resistance (based on [145]*)*

$$R_{si} = \frac{\sum_{j=1}^{n}(T_{ij} - T_{sij})}{\sum_{j=1}^{n} q_i} \left[\frac{m^2K}{W}\right] \quad \text{(A.6)}$$

where:

R_{si}	internal thermal surface resistance [m^{2}K/W]
q_i	heat flow [W/m^2]
T_{ij}	internal air temperature [°C]
T_{sij}	internal surface temperature [°C]

Equation A.7: Average method to calculate the external thermal resistance (based on [145]*)*

$$R_{se} = \frac{\sum_{j=1}^{n}(T_{sej} - T_{ej})}{\sum_{j=1}^{n} q_i} \left[\frac{m^2K}{W}\right] \tag{A.7}$$

where:

R_{se} external thermal surface resistance [m²K/W]

q_i heat flow [W/m²]

T_e external air temperature [°C]

T_{sej} external surface temperature [°C]

Finally, the average thermal resistances calculated from the measured data are further applied to **Equation A.3**, providing the thermal transmittance of the component, to allow further calculations of thermal losses.

Annex V - Building thermography

The thermal camera works based on the concepts that any object above absolute zero emits electromagnetic radiation, that according to Planck radiation law, the intensity of the emitted radiation is a function of the wavelength for a fixed temperature, and finally that Stefan-Boltzmann law states that the total radiated energy of a black body is proportional to the body temperature to the power of four, as presented in **Equation A.8**.

Equation A.8: Stefan-Boltzmann-law

$$M = \sigma \times T^4 \left[\frac{W}{m^2}\right] \tag{A.8}$$

where:

M total energy radiated per unit of surface [W/m²]

σ Stefan-Boltzmann constant $5{,}67 \times 10^{-8}$ [W/m²K⁴]

T temperature [K]

Furthermore, the measurement range of thermal cameras used in building thermography is between 8 and 14 μm, because according to the displacement law of Wien, the peak radiation emitted in the range of temperatures of building physics is around 10 μm. Besides, it is also in this range that the spectral transmittance of the air is optimal, having less influence on the measurements of a certain surface.

The thermography measurement shows the temperature distribution of the surface, and they must be interpreted as such, considering influencing factors to achieve a meaningful interpretation.

Annex VI - Air exchange rate

Blower-door Test

The blower-door test is a method used to assess the airtightness of the building envelope, identify air leakages, and estimate natural infiltration rates. The diagnosis is conducted by establishing a pressure differential between the internal and external environments of the building. A high-powered, calibrated fan is installed at the entrance, directing air into or out of the building for this purpose. The fan generates an over- or under-pressure condition, forcing the air through the openings and fissures. The airtightness is determined by measuring the airflow and air pressure, since the tighter the building, the less airflow is needed to change the pressure level.

To reduce the influence of natural infiltration on the measurements, this test is performed using much higher pressure differences, where the reference value to compare the air exchange rate of different buildings is defined as 50 Pa. Although there are other methods to determine the air exchange rate at 50 Pa, in this study the Multi-Point Test is adopted.

The Multi-Point Test uses different pressure gradient values to determine the air exchange rate at 50 Pa, increasing accuracy, but also providing estimations on the leakage area of the building. Here 10 measuring points are defined, with the pressure difference values varying from 25 to 70 Pa. The measurements and calculations are done using the software TECTITE, under under-pressure conditions, following the norm EN 13.829. The volume flow at each pressure difference level is obtained from 100 measurements, establishing a correlation between the pressure gradient and the volume flow, which provides the volume flow at 50 Pa. This volume flow is then divided by the heated net volume of the analysed building to obtain the normalised air exchange rate at 50 Pa to be adopted in further analysis regarding the energy performance of the building.

Equation A.9: Normalised air exchange rate at 50 Pa

$$n_{50} = \frac{\dot{V}_{fan}}{V} \left[\frac{1}{h}\right] \qquad (A.9)$$

where:

n_{50}	number of times that the air changes per hour at 50 Pa [1/h]
$\dot{V_{fan}}$	airflow needed to create a change in building pressure of 50 Pa [m^3/h]
V	heated net volume [m^3]

Equation A.10: Air permeability at 50 Pa

$$q_{50} = \frac{\dot{V_{fan}}}{A_E}\left[\frac{m^3}{m^2h}\right] \tag{A.10}$$

where:

q_{50}	air permeability at 50 Pa [m^3/m^{2}h]
$\dot{V_{fan}}$	airflow needed to create a change in building pressure of 50 Pa [m^3/h]
A_E	surface area of the building envelope [m^2]

Equation A.11: Leakage flow at 50 Pa

$$w_{50} = \frac{\dot{V_{fan}}}{A_F}\left[\frac{m^3}{m^2h}\right] \tag{A.11}$$

where:

w_{50}	leakage flow rate at 50 Pa [m^3/m^{2}h]
$\dot{V_{fan}}$	airflow needed to create a change in building pressure of 50 Pa [m^3/h]
A_F	net floor area of the building [m^2]

From the n_{50} value it is possible to air exchange rate n under natural conditions as presented in **Equation A.12**, allowing correlation with results from other methods, such as the CO_2 concentration decay method.

Equation A.12: Air exchange rate calculated from n_{50}

$$n_{n_{50}} = 0{,}35 + n_{50}e + 0{,}05\left[\frac{1}{h}\right] \tag{A.12}$$

where:

$n_{n_{50}}$	air exchange rate under natural conditions [1/h]
0,35	minimum hygienic air exchange [1/h]
n_{50}	number of times that the air changes per hour at 50 Pa [1/h]
e	protection class coefficient defined on the RGD 2021 [74]
0,05	air exchange related to the use of the building [1/h]

Table A.2: Protection class coefficient (e) defined on the RGD 2021 [74]

Protection class coefficient (*e*)	**More than one exposed façade**
No protection: buildings on open land, tall buildings in town centres	0.10
Medium protection: buildings located in wooded areas or surrounded by scattered buildings, buildings on the outskirts of towns	0.07 (standard)
High protection: medium-rise buildings in town centres, buildings in forests	0.04

The protection class coefficient defined on the RGD 2021 is obtained according to the level of exposure of the buildings, when more than one façade is exposed to the outside weather, as presented in **Table A.2** [74].

CO_2 Concentration Decay Method

The estimation of the air exchange rate n using the CO_2 concentration decay method is realised by injecting a known concentration of a tracer gas – in this case, carbon dioxide – into the building. A fan is used to guarantee the homogeneity of the CO_2 concentration in the analysed volume, while a sensor measures the concentration of carbon dioxide over a certain period after the CO_2 source is removed. Provided that there is no more source of the tracer gas, the concentration decay is represented by **Equation A.13**, and the air exchange rate is calculated by **Equation A.14**.

Equation A.13: Concentration decay

$$C(t) = C_0 \exp\left(-n_t\right) \tag{A.13}$$

where:

$C(t)$	concentration variation over time t [ppm]
C_0	initial CO_2 concentration [ppm]
n_t	air exchange rate at a time t [1/h]

Since in a logarithmic scale the concentration varies in a line shape, the air exchange rate is obtained using **Equation A.14**.

Equation A.14: Air exchange rate CO_2 concentration decay method

$$n_{decay} = \frac{\ln C_0 - \ln C_{t_1}}{t_1 - t_0} \tag{A.14}$$

where:

n_{decay}	air exchange rate CO_2 concentration decay method [1/h]
C_0	initial CO_2 concentration [ppm]
C_{t_1}	CO_2 concentration at time t_1 [ppm]
t_0	time at the beginning of the measurements [h]
t_1	time at the end of the measured period [h]

Annex VII - Physical measurements

Elsys ERS Indoor Climate Sensor

The device developed by Elsys contains sensors for measuring air temperature, humidity, CO_2 and light, coupled with a LoRa radio module to diffuse the data. Table A.3 presents the comfort parameters measurements range, accuracy and resolution.

Table A.3: Indoor Climate Sensor Elsys ERS parameters measured range, accuracy and resolution [146]

Parameter	Range	Resolution	Accuracy
Air temperature [ºC]	0-40 °C	0.1°C	± 0.5 °C
Relative humidity [%]	0-100 %	0.1%	± 2 %
CO_2 [ppm]	0-2000 ppm	1 ppm	± 45 ppm
Light [lux]	4-2000 Lux	1 Lux	± 10 Lux

Temperature is measured using a thermistor, which varies its resistance with temperature changes, providing accurate readings. Humidity is measured using a capacitive humidity sensor, where changes in relative humidity alter the dielectric constant of a polymer or metal oxide layer, resulting in variations in capacitance that are converted into humidity readings. The sensor operates using non-dispersive infrared spectroscopy. It contains an infrared light source, and a detector positioned on opposite sides of a gas chamber. As air passes through the chamber, CO_2 molecules absorb specific infrared wavelengths, reducing the intensity of the detected light. Finally, illuminance is measured using a photodiode-based sensor, which converts light intensity into an electrical signal. The sensor detects visible light levels in lux and can be used to monitor lighting conditions in indoor environments.

The ERS Elsys climate sensor is a useful tool for remote indoor climate monitoring, offering real-time insights into temperature, humidity, CO_2 levels, and light conditions. Its LoRaWAN connectivity enables long-range and low-power data transmission. However, it strongly depends on the availability of a LoRaWAN network, and users must consider periodic sensor calibration and power management to ensure optimal performance.

Wöhler CDL 210 CO_2 sensor

The compact Wöhler CDL 210 CO_2 device is used to monitor key indoor climate parameters, including carbon dioxide (CO_2) concentration, temperature, and relative humidity, using the same measuring principles as the Elsys ERS.

Table A.4: Wöhler CDL 210 CO_2 Comfort Sensor parameters measured range, accuracy and resolution [147].

Parameter	Range	Resolution	Accuracy
Temperature [ºC]	-10-60 °C	0.1°C	± 0.6 °C
Relative humidity [%]	5-95 %	0.1%	± 5 %
CO_2 [ppm]	0-9999 ppm	1 ppm	± 50 ppm +/- 5%

While the Wöhler sensor is a reliable and precise tool for indoor air quality monitoring, periodic calibration is necessary to maintain accuracy over time. Furthermore, the accuracy of temperature and humidity readings may be affected by direct sunlight, proximity to heat sources, or exposure to extreme conditions. Despite some limitations, the sensor is a useful instrument for improving ventilation control and ensuring a comfortable indoor environment.

Comfort measurements ISO 7730 – Ahlborn sensors

Following the ISO 7730 standard further comfort measurements are obtained using a station equipped with a globe-thermometer, a humidity and temperature sensor, and a thermo-anemometer. The height of the sensors is approximate the same height than the head of a sitting person (approx. 1.10m), to evaluate thermal comfort in classrooms, as presented in **Figure A.4**.

The measuring station is equipped to collect data concerning air and mean radiant temperature (°C), which refers to the dry-bulb temperature of the indoor air, and the uniform temperature of surrounding surfaces, respectively. Air velocity (m/s) measures the movement of air, which affects heat loss from the body, and relative humidity (%) indicates the moisture content of the air, influencing evaporation and overall comfort.

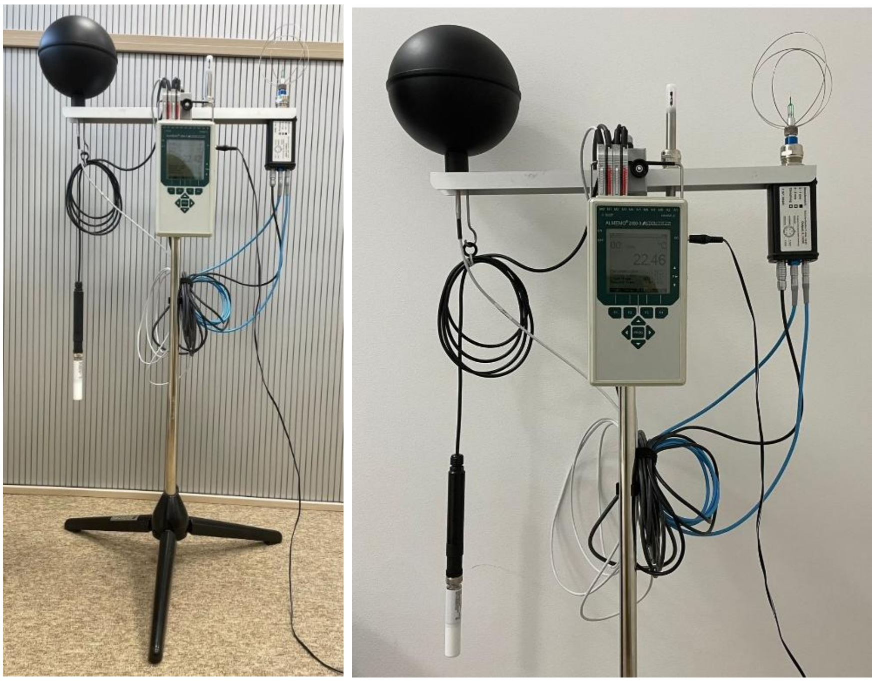


Figure A.4: Thermal comfort sensors (a) setup showing height (b) setup sensors detail

The station used in this study also includes CO_2 concentration (ppm) measurements, which is a useful parameter in various assessments. It is used to evaluate air quality, ventilation requirements, air exchange rates and presence.

The mean radiant temperature in measured using a device composed by a black copper globe with a standard diameter of approximate 15cm to absorb the radiant heat of surrounding objects equipped with a Pt100-sensor (Resistor based sensor), place inside the globe. The air space inside the black bulb is used to ensure that the absorbed heat is mixed inside the bulb, creating a uniform temperature.

The air humidity, temperature and pressure, are measured using the digital sensor with reference number FHAD46C4xAx. The multisensor module is made in stainless steel, protected filter cap and connected to a ALMEMO D6 plug.

The air velocity is monitored using a thermoelectric flow sensor FV A605 TA1, equipped with a heated miniature thermistor that is cooled down by the airflow. The change in resistance is a measure for the air velocity. As this measurement strongly depends on the ambient temperature a further precision NTC (Negative Temperature Coefficient) resistance is used to measure and automatically compensate the ambient temperature.

Table A.5: Ahlborn sensors measured parameters, range, accuracy and resolution [144][

Parameter	Range	Resolution	Accuracy
Mean radiant temperature [ºC]	(-100)-200 °C	0.01 K	± 0.2 K
Air temperature [ºC]	(-20)-80 °C	0.01 K	± 0.5 °C
Relative humidity [%]	5-98 %	0.1%	± 2 %
Atmospheric pressure [mbar]	700-1100 mbar	0.1 mbar	± 2.5 mbar
Air velocity [m/s]	0,01-1 m/s	0,001 m/s	±1.0%
CO_2 [ppm]	0-10000 ppm	1 ppm	± 100 ppm

The operative temperature is the sensed room temperature and can be calculated as the arithmetic mean of air- and radiant temperature.

The carbon dioxide concentration is measured using a digital probe FYAD 00-CO2 with an integrated signal processor. The sensor element, which operates with a non-disruptive infrared technology (NDIR), is protected from contamination by a replaceable filter cap.

Annex VIII - Perceived comfort questionnaires

Comfort is a subjective concept, and perceived comfort might present important variations for the same physical conditions. Comfort sensors are used to monitor the physical parameters, while users are submitted to a questionnaire to assess how they feel inside the buildings. These questionnaires are defined based on Roulet (2008) [15]. It aims to determine perceived comfort, but it also complements the physical measurements by including a section concerning the level of clothing insulation used in further calculations, as described in **3.3.5 Comfort parameters**.

The questions are divided in two groups. The first refers to the perceived indoor climate, while the second evaluates the perception of control with regards to the stated conditions.

The questionnaires are administered in classrooms where physical comfort parameters are monitored. To account for seasonal variations in perceived comfort, the questionnaires should be distributed four times per year. The aim is simply to compare the comfort measurements with the perceived comfort for the general users in a building under different meteorological conditions.

Comfort questionnaire

In the following, we will ask questions regarding the perceived comfort in the room you are currently in (Room: ___Building: ___)

Clothing you are currently wearing:

Feet				
Socks	☐ no	☐ thin	☐ thick	☐ wool
Shoes	☐ no	☐ light	☐ outdoor	☐ winter-/boots
Intermed. Cloth.				
Underwear	☐ no	☐ short	☐ long	☐ heavy tissue
T-shirt	☐ no	☐ short sleeves	☐ long sleeves	☐ heavy tissue
Shirts/blouses	☐ no	☐ shoulder free	☐ short sleeves	☐ long sleeves
Outer clothing				
Pants	☐ no	☐ tight fit	☐ loosely falling pants	☐
Dresses	☐ no	☐ long sleeves	☐ heavy tissue	☐
Skirts	☐ no	☐ short	☐ knee length	☐ ankle length
Pullovers	☐ no	☐ short sleeves	☐ long sleeves	☐ turtleneck
Jackets	☐ no	☐ heavy	☐ suit jacket	☐

How do you feel overall today?

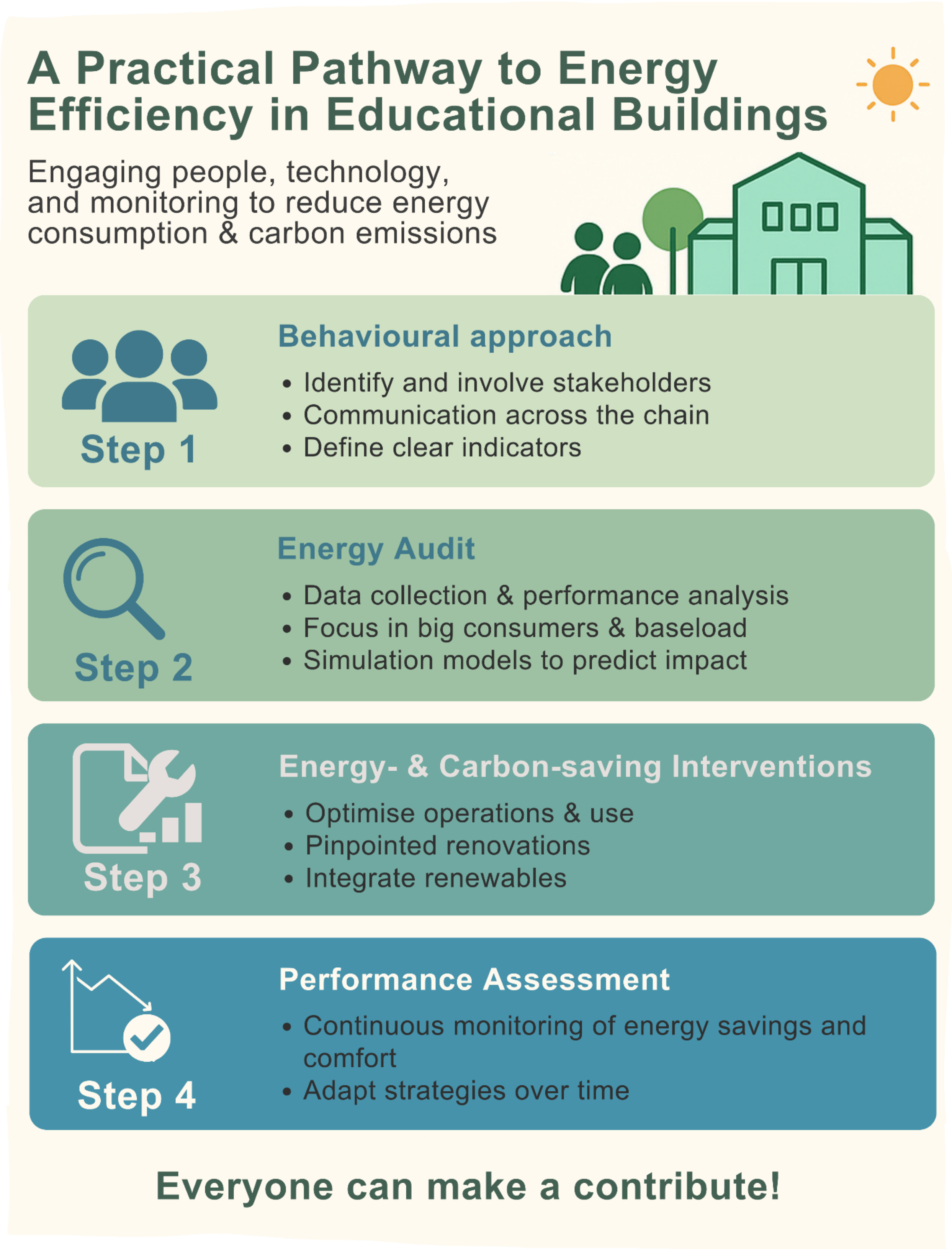
Very bad						Very good
☐	☐	☐	☐	☐	☐	☐

How do you rate the indoor climate in this seminar room?

1. Warm	☐	☐	☐	☐	☐	☐	☐	Cold
2. Dry air	☐	☐	☐	☐	☐	☐	☐	Humid air
3. Fresh air	☐	☐	☐	☐	☐	☐	☐	Used air
4. Uncomfortable temperature	☐	☐	☐	☐	☐	☐	☐	Comfortable temperature
5. Bright	☐	☐	☐	☐	☐	☐	☐	Dark
6. Indoor climate overall good	☐	☐	☐	☐	☐	☐	☐	Indoor climate overall bad
7. Air quality overall good	☐	☐	☐	☐	☐	☐	☐	Air quality overall bad
8. Acoustics overall good	☐	☐	☐	☐	☐	☐	☐	Acoustics overall bad
9. No draft at all in the room	☐	☐	☐	☐	☐	☐	☐	Very strong draft
10. No disturbing smell in the room	☐	☐	☐	☐	☐	☐	☐	Very disturbing smell
11. I would like to turn off the ventilation system completely	☐	☐	☐	☐	☐	☐	☐	… to turn on at max. power the ventilation system
12. I am not satisfied at all with the indoor climate	☐	☐	☐	☐	☐	☐	☐	… very satisfied with the indoor climate
13. The indoor climate is not important at all for me personally	☐	☐	☐	☐	☐	☐	☐	the indoor climate is very important for me personally

I would like to have	Very much			Neither nor			Very much	
14. The temperature colder	☐	☐	☐	☐	☐	☐	☐	Warmer
15. Reduce draft	☐	☐	☐	☐	☐	☐	☐	More draft
16. Windows less open	☐	☐	☐	☐	☐	☐	☐	Windows more open
17. Less light	☐	☐	☐	☐	☐	☐	☐	More light

Annex IX - Framework infographic



List of Publications

1. E. Doherty, D. Brychkov, N. Romero Herrera, E. McLoughlin, N. Roudil, S. Smit, S. Maas, F. Gauthier, E. Clifford, and B. Delmonte, "Integrating technology, education and practice to change energy behaviours in schools", in Proceedings CLIMA 2022 Conference, doi: 10.34641/clima.2022.166. [91]
2. D. Brychkov, G. Goggins, E. Doherty, N. Romero, N. Roudil, A. Di Trani, A. Singh, S. Smit, E. McLoughlin, R. de Castro Rodrigues Lima, S.M. Günbay, B. Delmonte, A. Hill, C. Domegan, and E. Clifford, "A systemic framework of energy efficiency in schools: experiences from six European countries", Energy Efficiency, vol. 16, no. 4, Apr. 2023, doi: 10.1007/s12053-023-10099-4. [90]
3. B. Delmonte, S. Latz, J. Youmbi, and S. Maas, "Impact of grey energy on optimal wall insulation thickness", Bauphysik, vol. 46, no. 1, p. 1, Feb. 2024, doi: 10.1002/bapi.202300021. [20]
4. B. Delmonte, E. Doherty, and S. Maas, "Energy savings potential of socio-technical interventions in secondary schools", in Proceedings Bauphysiktage in Weimar 2024, 2024. doi: 10.25643/dbt.59917. [99]
5. B. Delmonte and S. Maas, "The Impact of Optimised Set Values in Educational Buildings to Reduce Energy Consumption and Carbon Emissions", Sustainability, vol. 17, no. 7, p. 2792, Mar. 2025, doi: 10.3390/su17072792. [105]
6. C. Ribeiro, B. Delmonte, J. Sliepen, and S. Maas, "Techno-Economic Analysis on Implementing Hydrogen in a Combined Heat and Power Plant in Luxembourg to Reduce Carbon Emissions", Sustainability, vol. 17, no. 8, p. 3369, Apr. 2025, doi: 10.3390/su17083369. [60]
7. S. Latz, A. Thewes, B. Delmonte, and S. Maas, "Ein Luxemburger Leitfaden für die Planung von Innendämmprojekten durch Messungen und Simulationen", Bauphysik, vol. 47, no. 3, pp. 182–204, 2025, doi: https://doi.org/10.1002/bapi.202500008. [117]