HeriTACE

Baseline BES-models

Deliverable D3.3

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Abbreviations and acronyms

Acronym	Description
KPI	Key Performance Indicators
PEF	Primary Energy Factor
PEU	Primary Energy Use
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
RH	Relative Humidity
TMY	Typical Meteorological Year
TRY	Test Reference Year
Ta	Indoor air temperature
RH	Relative humidity
DHW	Domestic Hot Water
BES	Building Energy Simulation
ARPA	Agenzia Regionale per la Protezione dell'Ambiente (regional environmental protection agency)
NMBE	Normalized Mean Bias Error
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error
PV	Photovoltaic
PC	Pre-renovation case-study
RB	Renovation baseline
PB	Pre-renovation baseline
MCT	Middle-class townhouse
MH	Modest house
PM	Private mansion
MFT	Multi-family townhouse
CLO	Clothing level
RMT	Running mean temperature
MET	Metabolic rate
FEM	Finite Element Method

Executive Summary

Project context

The deliverable documents the development and validation of multi-zone Building Energy Simulation (BES) and Indoor Environmental Quality (IEQ) models for the HeriTACE case studies and archetypes, in line with Task T3.2.2, and provides a complete description of the modelling methodology, including zoning strategy, boundary conditions, climate files, occupancy and internal gains, HVAC operation, infiltration, and envelope characterisation. The pre-renovation and renovation baseline scenario building envelope and HVAC systems (as defined in D5.5) were modelled, and the models were validated using the energy and IEQ monitoring data collected in Task T3.1. The validation was carried out through different approaches depending on the type and quality of available monitoring data. These complementary validation pathways ensured that each model was assessed using the most suitable method for its data context, resulting in reliable, documented baseline models and performance results that serve as the foundation for subsequent renovation scenario assessments within HeriTACE.

It should be noted that the baseline renovation scenarios represent current-day, standard renovation practices, which typically entail a relatively high impact on heritage values. While these baseline renovations provide a useful reference for performance benchmarking, they are not always feasible or acceptable in heritage contexts due to conservation constraints. This underlines the need for more tailored and context-sensitive renovation solutions, such as those investigated within HeriTACE, which are expected to achieve a more balanced trade-off between energy savings, indoor environmental quality improvements and the preservation of cultural and heritage values. The results of those HeriTACE renovation scenarios will be documented in subsequent deliverable D3.9.

It should be noted that the simulation results show recurring trends, highlighting shared challenges and opportunities to improve the performance of European heritage buildings, hereafter summarized.

Outcomes

Energy Performance

All countries exhibit a strong and consistent improvement in energy performance following envelope-oriented renovation measures. Introducing insulation in walls, roofs, and floors; replacing windows; reducing infiltration; and improving system efficiencies lead to typical primary energy savings exceeding 50% relative to pre-renovation conditions.

The magnitude of improvement is especially pronounced in Italian and Belgian case studies, where traditional uninsulated masonry walls, outdated windows, and high air leakage rates form a weak baseline. These characteristics make envelope retrofits highly effective. However heritage constraints restrict the extent of possible interventions.

In Norway and Estonia, the drivers of energy demand are different, dominated by long and severe winters. Here, traditional timber log buildings (Norway) and mixed wooden–brick apartment blocks (Estonia) show marked sensitivity to improvements in airtightness, window performance, and thermal bridge reduction. Even moderate envelope upgrades deliver substantial energy savings because they significantly reduce heat loss during prolonged heating seasons. Across all countries, envelope improvements and infiltration reduction remain the most impactful levers for reducing heating demand, regardless of construction type or climatic conditions.

Thermal Comfort

Winter comfort improves significantly in all countries after renovation. Better insulation and window performance reduce radiant temperature asymmetries, eliminate cold downdrafts, and allow indoor air temperatures to remain within the Category II comfort band (defined by EN 16798-1:2019) for a much larger portion of the heating season. This improvement is most pronounced in Italy, where many pre-renovation envelopes are poorly insulated and heat loss is substantial. In Norway and Estonia, the improved envelope stabilises indoor temperatures and mitigates cold-surface effects associated with extreme winter conditions.

Summer comfort, however, becomes a context-dependent concern. In Italy, tightened envelopes combined with warm summers and limited shading possibilities increase the risk of overheating. In Belgium, internal heat gains and dense urban configurations contribute to elevated operative temperatures, particularly on upper floors of deep terraced houses. These trends show that while winter comfort can be reliably addressed with envelope measures alone, summer comfort often requires integrated strategies such as shading, passive cooling, night ventilation, or carefully designed mechanical cooling solutions compatible with heritage preservation.

Relative Humidity (RH)

RH patterns remain generally within the recommended 30–70% range for most of the year in all countries. High-humidity periods decrease after renovation due to improved thermal stability and reduced cold-surface condensation risks, an important factor for protecting historic materials. Low-humidity episodes, however, become more frequent in cold climates when MVHR systems introduce very dry outdoor air during winter. This suggests that, in northern locations, moisture-sensitive ventilation strategies or complementary humidification may be needed to preserve both occupant comfort and material integrity.

Indoor Environmental Quality (IEQ)

While energy performance improves across all cases, the models reveal an inherent ventilation-related challenge in heritage renovation. As buildings become more airtight, whether through window replacement, insulation layers, or air leakage control, their reliance on deliberate ventilation strategies increases. In pre-renovation conditions, unintentional infiltration often provided a substantial share of fresh-air supply. After renovation, this background ventilation is reduced, and indoor CO_2 concentrations increase, particularly in bedrooms during night-time occupancy.

This issue is most evident in Italy and Belgium, where airtightness improvements are large and mechanical ventilation is not always included in renovation baselines. In scenarios where mechanical ventilation with heat recovery is added (e.g Belgium), CO_2 concentrations remain within acceptable comfort categories throughout the year, demonstrating that IAQ can be fully safeguarded when ventilation systems are modernised alongside the envelope.

The cross-country comparison thus underscores a central principle: airtightness improvements, though essential for energy efficiency, must be paired with adequate ventilation if IEQ is to be preserved. The HeriTACE renovation scenarios to be developed in subsequent tasks, will investigate ventilation solutions that are also feasible for integration in the heritage context.

Conclusion

In summary, the simulations show that envelope-focused renovations are highly effective in reducing energy demand and improving winter comfort across a wide variety of heritage contexts. However, these benefits must be balanced with well-designed ventilation strategies to avoid compromising indoor air quality and humidity conditions, particularly in airtight post-renovation buildings. Summer comfort also requires special attention in warmer climates or dense urban contexts. The validated baseline models developed through this work provide a robust, cross-country foundation for the evaluation of optimized renovation scenarios in subsequent HeriTACE tasks.

1. Introduction

The HeriTACE project proposes a comprehensive renovation methodology tailored to heritage townhouses, balancing preservation with modern performance and sustainability needs. The approach ensures long-term conservation of cultural value while improving indoor environmental quality, enhancing energy efficiency and allow a shift away from fossil fuels. It promotes the adoption of renewable and residual energy sources, supports integration with local energy grids and prioritises sustainable, circular material use to minimise environmental impacts. Cost-effectiveness and affordability over the building's lifetime are also central objectives. To deliver these goals, HeriTACE project will develop optimised renovation actions across three interconnected scales: individual components and systems, the building as a whole and its surrounding neighbourhood. This multi-scale strategy allows targeted measures at each level to contribute to an overall optimised renovation outcome.

In this regard, multi-zone building energy and Indoor Environmental Quality (IEQ) simulation models are developed for selected archetypes located in diverse climate zones, capturing the thermophysical behaviour and indoor environmental conditions of buildings under both pre-renovation and post-renovation scenarios. These scenarios include variations in the building envelope and HVAC system configurations, allowing for a comprehensive assessment of the impacts of retrofit interventions as reported in D5.4 and is the fundamental work for the later assessment of retrofit interventions reported in D3.1 and D2.2.

The pre-renovation case-study scenario, based on real user behaviour and actual operating conditions, is employed exclusively for the calibration and validation or verification of the baseline archetype simulation models. This process is performed by aligning the simulated outputs with high-resolution energy consumption and IEQ-monitoring data collected during Task T3.1, as reported in Deliverable D3.2, to ensure model accuracy, choice of modelling assumptions and robustness.

Following validation or verification, the baseline archetype models are developed by applying standardized inputs (e.g. uniform assumptions for the user profile) as described in D5.4 of the HeriTACE project, enabling consistent and comparable assessments across different baseline archetype models.

It is important to note that the baseline renovation scenarios reflect contemporary, conventional renovation approaches, which generally result in a comparatively high impact on heritage values. Although these baseline interventions serve as a valuable benchmark for performance comparison, they are not always appropriate or practicable in heritage settings due to conservation requirements and restrictions.

Subsequently, the standardized models are used to simulate the implementation of a conventional renovation approach, in accordance with the typical national renovation practices in each country represented in the study. This methodological framework allows for the evaluation of renovation impacts under harmonized usage conditions while respecting regional retrofit norms.

2. Methodology

The methodology adopted for this study follows a structured and multi-step approach aimed at developing reliable dynamic energy simulation models, enabling the evaluation of the baseline scenarios with respect to both performance and heritage constraints.

A detailed model was developed, to enable an accurate assessment of thermal behaviour, and indoor air quality was analysed through contaminant transport simulations to capture the movement and transformation of pollutants inside the building. To represent building behaviour realistically, a multi-zone approach was adopted, dividing each dwelling into separate thermal zones. Weather files specific to the study locations and a Typical Meteorological Year (TMY) were used to ensure representative climate conditions. Standardized occupancy profiles, internal gains, heating and cooling schedules, natural ventilation behaviour, domestic hot water use and appliance loads were incorporated to reflect typical household conditions. The modelling also accounts for contextual influences such as surrounding buildings, shading and thermal interactions between neighbouring structures. Thermal bridges and infiltration were explicitly considered through adjusted envelope properties and specific airtightness scenarios. These elements provide a robust framework for evaluating the performance of the baseline scenarios and for supporting reliable comparison across renovation scenarios.

The process begins with a thorough preliminary analysis of the case study buildings carried out (D5.1, D5.2 and D3.2) and the different baseline scenario shown in deliverable D5.4. This includes the identification and characterization of construction materials, focusing on their thermal properties and the current condition of the building envelope. Simultaneously, existing HVAC systems are examined to understand their operational characteristics, efficiencies, and integration with the building fabric. A core component of the methodology involves the calibration and validation or verification of the simulation models to ensure they reflect representative building performance. This is achieved through the acquisition of high-resolution indoor and outdoor data collected via dedicated monitoring campaigns reported in deliverable D3.2. The collected data support an iterative refinement process, where models are progressively adjusted to align simulated outputs with observed conditions.

In the following sections, the procedure for model calibration/validation or verification of the simulated baseline scenarios and the main outputs compared are explained.

2.1. Definition of the baseline scenarios

Overall three distinct modelling scenarios will be simulated:

- **Pre-renovation Case-study (PC) scenario**: this is a model for the calibration/validation and verification procedure against a measured case-study. Such a model reflects the current, as-is, state of the building, including real occupant behaviour and existing system operation. To do this, a weather file of the same year of the measured data used for the calibration/validation and verification procedure is needed;

- **Pre-renovation Archetype Baseline (PB) scenario:** this reflects the situation of the heritage building before a renovation takes place, typically assuming the last renovation occurred between 1990 and 2010, without recent EPBD-inspired energy measures. More in detail, in this scenarios, the building geometry is a representation of the **Archetype**. However, a broader range of baseline scenarios (e.g. different technological components and HVAC) has been identified in order to capture a wider spectrum of potential starting situations of the archetype on pre-renovated state (according to the D5.4.);

- **Renovation Archetype Baseline (RB) scenario:** this scenario is based on the current common practice renovation, where interventions are implemented step-by-step while adhering to local temporary energy requirements and heritage restrictions. More in detail, this scenario models the building after the application of traditional (non-heritage-specific) renovation practices common in each respective country, including updated envelope and HVAC technologies (as described in D5.4).

All configurations in PB and RB scenarios are analysed under harmonized and conventional usage profiles, ensuring comparability across the different cases. For the climatic input, the TMY file will be employed.

It should be noted that, the simulation studies for the different countries are conducted using various software tools (e.g. EnergyPlus, Dymola, IDA ICE) which, according to the literature review provided by Akkurt GG, et al. (2020), have demonstrated high reliability. Reported deviations among these tools are generally small, confirming their suitability for cross-country comparative analyses.

These baseline scenarios simulated in this report provide the foundation for modelling subsequent optimized HeriTACE renovation strategies, which aims for significant energy use reduction and the use of fossil-free energy sources.

2.2. Model Calibration/ Validation or Verification Approach

A critical step of the simulation methodology involves the rigorous calibration/validation or verification of the developed dynamic baseline simulation models for each archetype. Given the variability in the equipment and usage profiles of historic buildings, the approach to calibration and validation is adapted according to the presence or absence of active heating and cooling systems.

Furthermore, in response to the large number of case studies considered, two distinct calibration and validation approaches have been developed: *Case-study level calibration/validation* and *Archetype level verification*. These are differentiated by their level of accuracy: the first characterized by high accuracy, and the other by a medium level of accuracy, allowing for methodological flexibility depending on the data availability and complexity of the country specific situation.

2.2.1. Case-study level calibration/validation

The high accuracy calibration level is based on the flowchart in Figure 2.1, differentiating between cases where the building is equipped with an HVAC system and those where it is not, as described hereafter.

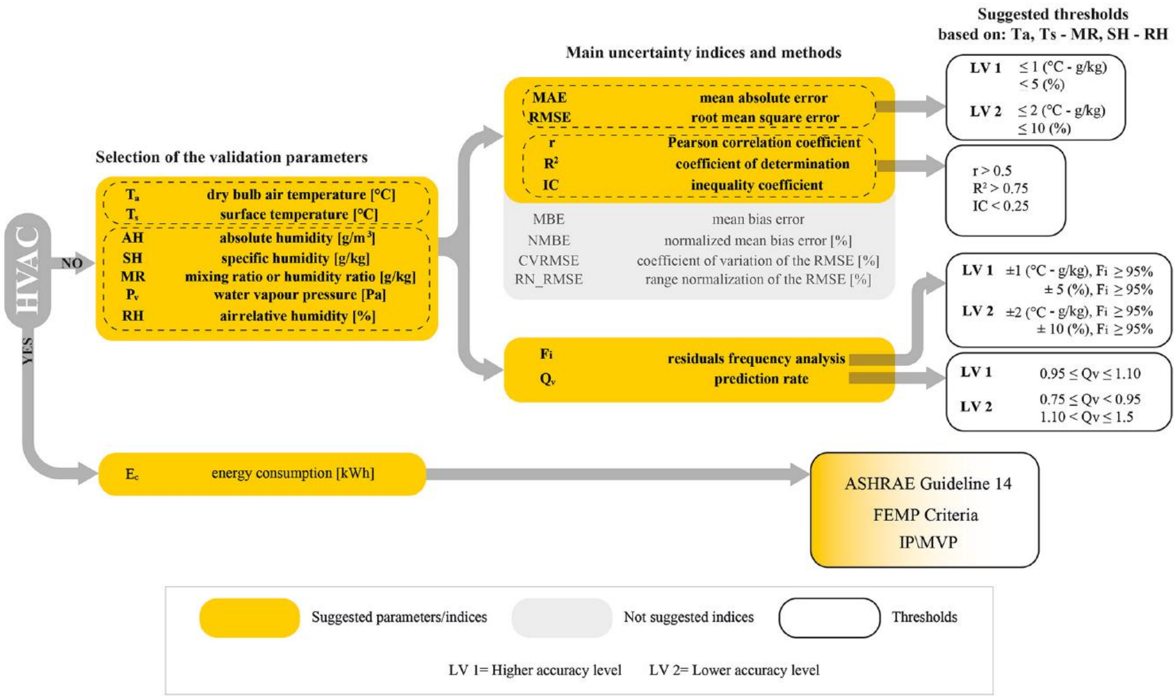


Figure 2.1 flowchart showing the procedure for validating simulation models (Huerto-Cardenas, H.E., et al. (2020)

By adopting this dual-path validation approach, tailored to the building's technical configuration, the study ensures that all models, regardless of HVAC presence, are grounded in empirical evidence and can serve as robust tools for scenario analysis and retrofit strategy development.

Calibration and validation with HVAC systems

In buildings where heating and/or cooling systems are operational, the simulation models can be calibrated and validated using measured energy use data. In this context, the validation process adheres to ASHRAE Guideline 14, which provides standardized performance metrics to assess the accuracy of building energy models. Specifically, two principal indicators are employed:

- Normalized Mean Bias Error (NMBE): Quantifies the average bias between simulated and measured values, normalized by the mean of the measured data;
- Coefficient of Variation of the Root Mean Square Error (CVRMSE): Assesses the magnitude of the model's prediction error relative to the mean of observed values.

These metrics allow for an objective evaluation of model performance, ensuring compliance with established statistical thresholds and enabling a high level of confidence in the simulation outputs. More in detail, the model validation can be performed on either a **monthly** or **hourly** basis, depending on the available measurement data and the intended level of accuracy. The ASHRAE14 guideline provides specific performance thresholds for each temporal resolution, recognizing that hourly validation captures more detailed dynamic behaviour but allows for higher statistical variability, while monthly validation is less granular but typically results in tighter error margins. The different thresholds are reported hereafter.

Data type	Index	ASHRAE Guideline 14 thresholds
Monthly	NMBE (%)	±5
	CVRMSE (%)	15
Hourly	NMBE (%)	±10
	CVRMSE (%)	30

Table 2.1 Thresholds for the validation of simulation models proposed by ASHRAE Guideline 14

Calibration and validation without HVAC systems

In the absence of active thermal conditioning systems, energy consumption data are either unavailable or insufficient for traditional validation. In such cases, the validation methodology shifts toward the comparison of **microclimatic parameters**, primarily:

- Indoor air temperature (Ta);
- Relative humidity (RH).

For such applications, a variety of performance indicators and threshold values can be used to evaluate the agreement between measured and simulated indoor environmental conditions. In this study, the recommended validation framework is based on the work done by Huerto-Cardenas, et al. (2020).

This work provides a comprehensive synthesis of best practices and scientifically grounded criteria for validating hygrothermal models in heritage contexts. It emphasizes the importance of dynamic calibration, taking into account seasonal variations, thermal inertia, and moisture buffering effects typical of traditional building materials. The suggested methodology includes quantitative indicators (e.g., mean deviation, root mean square error, and correlation coefficients) alongside qualitative assessment tools, enabling a holistic understanding of model reliability.

2.2.2. Archetype level verification

In case the baseline model description is not a one-to-one representation of one of the specific measured case-studies is it more valuable to compare and verify the outcome of a general archetype baseline model with the overall insights in the measurements of all related case-study measurements. This allows the correct development of the baseline performance and compare where the impact of general assumptions lie compared to the measurements which are driven by very personal occupancy and building usage patterns that can differ from the baseline.

The verification of the archetype model will be done by comparing the simulation results for indoor temperature, CO_2 levels and energy use with the measured cases that are of the same archetype. The goal is clearly not to get a perfect match between the simulation results and the measurements but rather use the distributions of the studied parameters to verify the modelling assumptions and outcomes.

The result is a verification of the baseline archetype model, providing confidence that the simulated results hold value and capture the specific dynamic indoor condition of the archetype buildings accurately.

2.3. Output from the simulations

The main outputs that will be assessed throughout the different regions for both the pre-renovation baseline and renovation baseline scenarios are:

- **Energy Need**: represents the theoretical energy demand required for services like heating, cooling, or domestic hot water (DHW) to maintain desired indoor conditions, excluding any system losses or inefficiencies. This need is determined by summing the heat losses (transmission and ventilation) and subtracting the internal and solar gains over the calculation period. It is expressed in kWh/m^2 year;
- **Energy Delivered**: represents the actual energy supplied by the technical building systems (such as heat pumps or boilers) at the system boundary to meet the energy needs, reflecting system performance and losses. Energy Delivered is expressed in kWh/m^2 year by dividing the Energy Need by the overall efficiency (η_{sys}) of the technical system, where η_{sys} accounts for the efficiencies of the generation, distribution, and emission sub-systems;
- **Primary Energy Use:** which defines energy that has not been subjected to any conversion or transformation, encompassing both non-renewable and renewable energy sources. This output is calculated in yearly kWh/m^2 of climatized floor area by summing the delivered energy for each carrier (such as electricity or gas) multiplied by its respective Primary Energy Factor (PEF). For this report, the PEF as reported in D5.5 are used, which are also the PEF described in ISO 52000. For fossil fuels, a PEF of 1.1 is assumed, for electricity a PEF of 2.3.
- **Thermal Comfort**: which assesses whether the indoor thermal conditions meet the expected comfort level, often designated as Category II (CAT II), defined by EN 16798-1:2019. The output is evaluated by measuring the number of hours the operative temperature falls inside the CAT II design range (or better);
- **Relative Humidity (RH)**: which evaluates the deviation of indoor RH from the ideal range of 30–70%. The final performance is assessed by calculating the number of hours where the RH is within, above or below the ideal range;
- **Indoor Air Quality (IAQ)**: which uses CO_2 concentration as an indicator of whether ventilation rates are satisfactory. Design values for CO_2 concentration above the outdoor level are set for residential spaces like living rooms and bedrooms in CAT II (see EN 16798-1:2019 and EN 16798-2:2019). The final performance is assessed by calculating the number of hours where the CO2 is within a certain IEQ category.

3. Baseline simulations

In the following chapter the results from the baseline simulations for each country are shown.

3.1. Italy

In Italy three building archetypes will be modelled in order to estimate the expected energy performances, comfort and IAQ performance through dynamic state simulations. This model makes it possible to reliably reproduce the energy behaviour of the structure and to estimate the savings associated with the hypothesised efficiency measures. In the Italian case studies, the model calibration/validation procedure was used instead of the verification process, as this was the most appropriate procedure in terms of both the number of case studies, with respect to the other countries, and simplicity of the conditions of use.

3.1.1. General assumptions

Coupled BES-IAQ

The model geometry was created using Rhinoceros software for 3D modelling and Grasshopper (with the Ladybug Tools plug-in) for the energy assessment. The simulations carried out with this software are based on the EnergyPlus calculation engine, which allows high-precision energy simulations to be carried out in a dynamic state. Regarding IAQ simulations, CONTAM software has been used. This tool allows for the analysis of contaminant concentrations by modelling how pollutants are transported, transformed, filtered, deposited or generated within the building.

Multi-zone approach

Based on the multi-zone approach, each room of the building is treated as a separate zone, including both living spaces and hallways. Only the cellar and the attic are considered as single zone. This number of thermal zones for each archetype are shown in the following table.

Archetype	**Amount of zones**
Palazzetto	32
Gothic lot	27
Extended building	23

Table 3.1 Number of zones in each Italian archetype model

Weather data

In order to perform dynamic energy simulations, climate data of the specific location that is investigated is required. Within EnergyPlus engine, a weather file containing different parameters (such as temperature, relative humidity, atmospheric pressure, direct and diffuse solar irradiation, wind speed and wind direction, etc.) with hourly time step is necessary.

Two main weather files were used to analyse the Italian archetypes. The first was specific to 2024, which is the year when temperature and relative humidity measurements were taken during the monitoring campaign, as well as when electricity bills were collected. This file was mainly used to perform the model calibration/validation procedure. More in detail, the external climate data were collected from the Regional Environmental Protection Agency (ARPA) meteorological station (Mantova - S. Agnese) located in the historic centre of Mantua, as shown in the figure below. This meteorological station recorded temperatures, relative humidity, horizontal solar radiation and wind speed/direction with hourly time step.

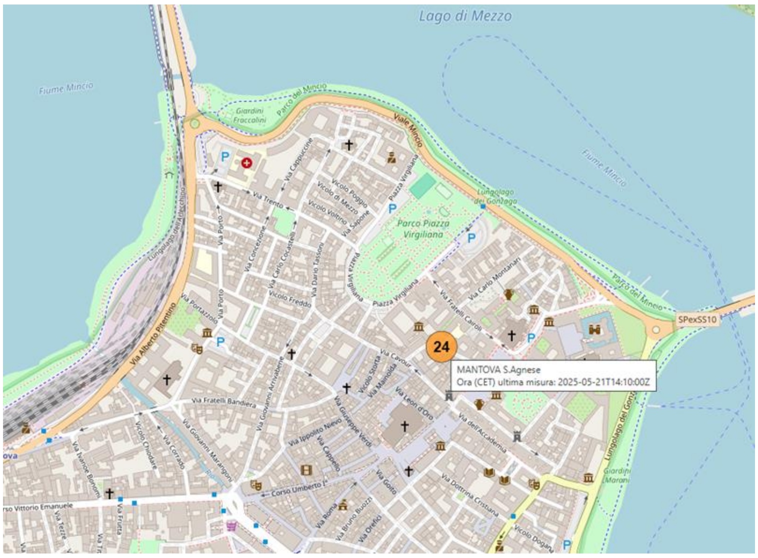


Figure 3.1 Location of the ARPA weather station adopted for the outdoor climatic data.

The second climate file used is a TMY, relative to the city of Verona (Valerio Catullo Airport), which is about 30 km far from Mantua. This weather file has been selected, since there is no specific TMY available for Mantua. Moreover, to better reflects the current climate conditions, was chosen a weather file relative to the years 2009-2023.

Occupancy

For the baseline scenarios, in all case studies, each floor was considered to be inhabited by an average four-person family. Different profiles were considered for the living room, bedroom, kitchen and bathroom in the various spaces that make up the apartments. Therefore, a standardized full-occupancy profile is applied to all building archetypes, assuming that every room is in use (with an exception for the attic and the cellar) and all occupied rooms are heated, as defined in D5.4. More in detail, about the sources of the input provided, internal gains are based on the boundary conditions provided in WUFI, which specify the number of occupants, daily presence, bathrooms, showers, and appliance specifically for four-person family. Heat gains follow guidelines including VDI 2078/DIN 1946-2 and reference values for typical household appliances. These sources ensure consistent and comparable internal loads across all simulated scenarios.

Heating and cooling

As already described in D3.2, the heating period for the various building case studies is schedule according to the standard (UNI-TS 11300) for Climate Zone E in Italy, which spans from October 15 to April 15, with heating allowed for 14 hours per day with a setpoint of 20°C. While cooling can be considered active when necessary, with a setpoint of 26°C.

Occupancy related assumptions

The impact of occupants, such as opening windows, the use of electrical appliances/artificial lighting, the use of DHW, etc., was considered in the model by defining some schedules for the various activities. Specifically, the following was considered for each parameter:

- Window opening behaviour: in the simulation, two different window-opening strategies for winter and summer conditions have been adopted. During the winter period, it was assumed that occupants open the windows only briefly at specific times of the day, early morning at 06:00, lunchtime at 13:00, and in the evening at 18:00, reflecting short, intentional ventilation events aimed at maintaining indoor air quality while minimizing heat loss. In contrast, summer ventilation was driven by outdoor temperature conditions. Windows were opened when the exterior temperature was within a comfortable range of 20°C to 26°C, provided that the temperature difference between indoors and outdoors was at least 1°C. This approach allowed natural ventilation to operate when it could effectively contribute to cooling, thereby reducing the need of air conditioning system and improving indoor comfort during warm months;

- Domestic hot water (DHW): the calculation of domestic hot water was performed considering a total number of 4 people per each floor of the case studies. A daily water consumption of 60 l/person was considered for each person, while the average inlet and outlet water temperatures were considered to be 15°C and 45°C, respectively. These values were assumed to be constant throughout the year;

- Appliances & lighting: for the main rooms, the heat gains from appliances and lighting is defined, both for convective as for radiative heat gains based on the specific profiles;

- Moisture production of activities: the latent loads from occupants (e.g. the moisture emitted by respiration and skin evaporation) are considered in the simulations through a moisture generation rate determined from the activity level assigned to each person and this water vapour is directly added into the zone's moisture balance. In such regard, the added vapour increases the humidity ratio and affects relative humidity, raising the latent cooling demand. The software continuously updates this moisture contribution during the simulation, so variations in occupancy or activity level directly influence the zone's latent loads;

- CO_2 production of activities: regarding CO_2 produced by people, a value of 20 l/h/person and 13.6 l/h/person was considered for awake and asleep people respectively, based on the specific profiles. CO_2 generation is based on occupant production rates for different activity levels according to EN 1679-1:2019.

Building context and obstructions

The buildings in the proximity of the case studies, both adjacent and opposite, were modelled considering their maximum volume to consider the shadows they generate. Similarly, other external shading elements such as eaves, dividing walls between properties, canopies, etc., which may affect the energy balance of the buildings, were also modelled. Regarding the walls adjacent to other properties, these were considered as adiabatic, as it is assumed that the neighbouring buildings are also heated/cooled under similar conditions.

Thermal bridges

To incorporate the effect of thermal bridges into the model, the wall U-values were adjusted to account for the additional heat losses associated with linear thermal bridge interactions. Linear thermal transmittance values (ψ) were assigned for the wall–floor and wall–window junctions for both the pre-renovation and renovation baseline scenarios. For the scenarios without insulation, the ψ-values used were 0.194 W/mK and 0.222 W/mK, respectively for the wall-floor and wall-window thermal bridge. While for the renovation scenarios with insulation, the corresponding ψ-values were 0.137 W/mK and 0.076 W/mK, respectively for the wall-floor and wall-window thermal bridge. These values were obtained preliminarily from an analysis of the construction nodes using the Finite Element Method (FEM) simulation. After applying these thermal bridge values, the wall U-value of the main exterior wall component were recalculated by modifying the thermal conductivity of the insulation layer for the two insulated scenarios, while for the remaining non-insulated cases the conductivity of the brick layer was adjusted. This approach ensures that the model captures the additional heat losses introduced by thermal bridges under both insulated and non-insulated conditions.

Air infiltration

Infiltration was modelled by incorporating the air-tightness values defined in D5.4 for each scenario. The air leakage rate estimated at 50 Pa ($m^3/s{\cdot}m^2$) was adjusted to the typical building pressure to reflect the specific airtightness of each case. Afterwards, for every room, the infiltration airflow (m^3/h) was calculated and weighed by considering the exposed window area (m^2) with respect to the total, allowing the air leakage to be scaled accurately based on the room's envelope characteristics. Finally, the Air Changes per Hour (ACH) were determined by dividing the calculated infiltration airflow by the volume of each room. This procedure ensured a consistent and scenario-specific estimation of infiltration rates throughout the building.

3.1.2. Palazzetto

The Palazzetto archetype defines a 17th – 19th century buildings that resembles a Gothic lot but with a greater width, often with three or four floors including a mezzanine and basement. It includes a noble floor with higher ceilings, a rear courtyard, and sometimes L-shaped extensions. It reflects later historical evolutions and renovations. In both the pre-renovation and renovation baseline scenarios, the entire building is considered heated and occupied, except for the attic and cellar. As described above, each floor is considered occupied by a family of four. Furthermore, no changes to the spatial layout are expected in the renovation baseline. The main simulations carried out are described below.

Pre-renovation (as-is)

The case study involves a historical residential building located in Mantua (Italy), indicated as "Occ_A". The building dates back to the early 17th century and exemplifies the Palazzetto archetype. It comprises three floors above ground, a basement, and an attic, organized with a three-opening rhythm on the façade and lacking decorative embellishments. The total surface area of the building is approximately 512 m² (floor area: 471m²). The property is classified under the Palazzetto archetype and is located within the UNESCO buffer zone of Mantua.

Figure 3.2 View from above of the Occ_A case study

In detail, the energy model of the building under study consists of 31 thermal zones. These zones have been defined based on the functional distribution proposed in the design phase, with each zone representing areas that share similar usage, occupancy patterns, and thermal characteristics. This subdivision allows for a more accurate simulation of the building's energy performance. A visual representation of the completed energy model is provided below.

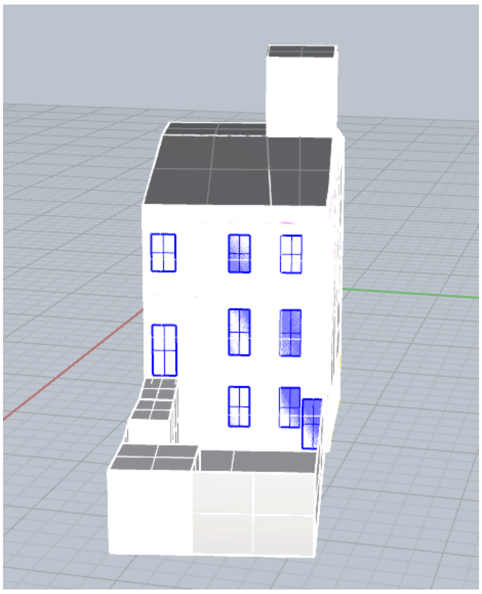


Figure 3.3 View of the BES model of building case study

The building was segmented (in the BES model) into individual floors and further divided into thermal zones, hereafter reported

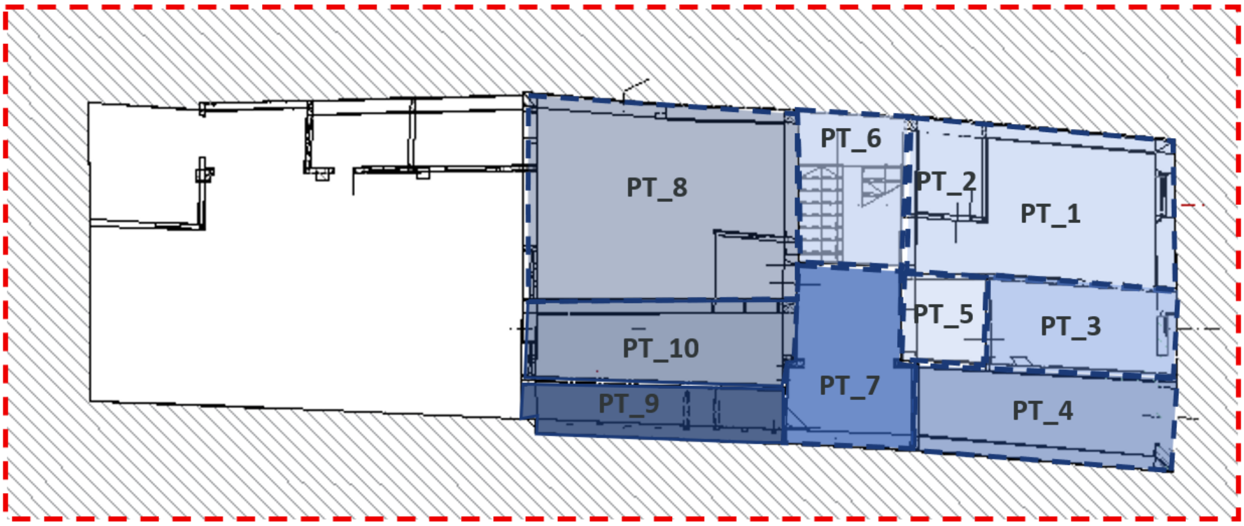


Figure 3.4 Detail of thermal zones with reference rooms code (Ground floor)

Space	Number of thermal zones	Code
Basement	1 zone	PT_1
Ground floor	10 zones	PT_1 to PT_10
First floor	8 zones	PP_1 to PP_8
Second floor	10 zones	SP_1 to SP_10
Attic	3 zones	ST_1 to ST_3

Table 3.2 Detail of thermal zones with reference rooms code

The building is constructed using solid brick masonry, with exposed wooden floors and a pitched roof supported by historic timber trusses. A rear internal courtyard or garden further improves the daylighting and thermal comfort of the adjacent interior spaces. A detailed classification of wall types was established, with thicknesses ranging from 0.1 to 0.5 meters.

Floor and roof assemblies were similarly characterized, with each component assigned relevant thermal properties such as thermal conductivity, density, and specific heat capacity. Window assemblies were assumed to be double-glazed with wooden frames, featuring a U-value of 2.9 W/m²·K. In attic spaces, windows were modelled as single-glazed with metallic frames, with an estimated U-value of 5.8 W/m²·K. Regarding the internal gains due to presence of people, electrical equipment and artificial lighting, these were considered null because the building was unoccupied during the monitoring campaign. On these bases, the model calibration and validation has been performed according to the methodology mentioned before, comparing the RH and T of the different acquired data with the ones resulting from the simulation. Adopting such process, a RMSE for air temperature lower than 2°C has been obtained

Results for Pre-renovation and Renovation baseline scenario

According to D5.4, the Pre-renovation baseline scenarios defined for the Palazzetto archetype are shown in the scheme below.

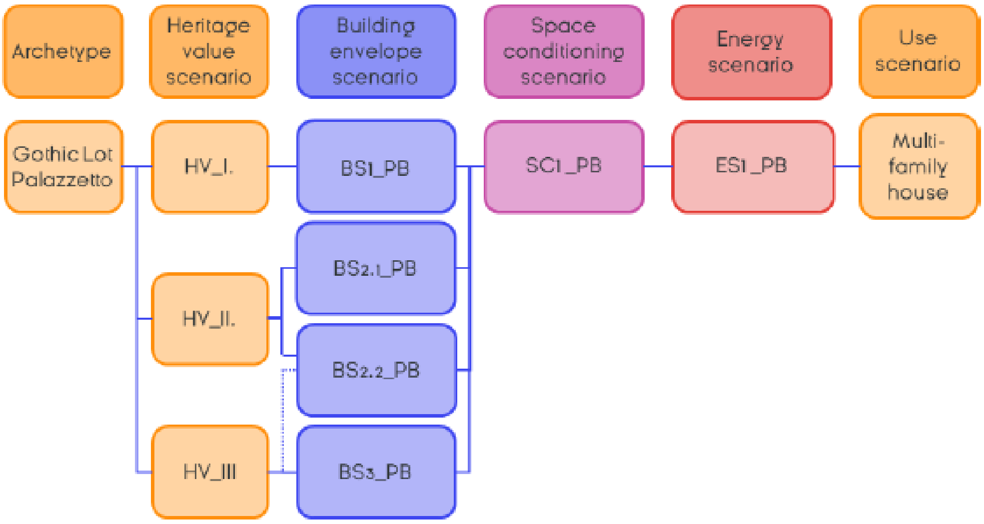


Figure 3.5 Overview of the Pre-renovation baseline scenarios for the Palazzetto archetype

Similarly, based on D5.4, the Renovation baseline scenarios defined for the Palazzetto archetype are shown in the scheme below.

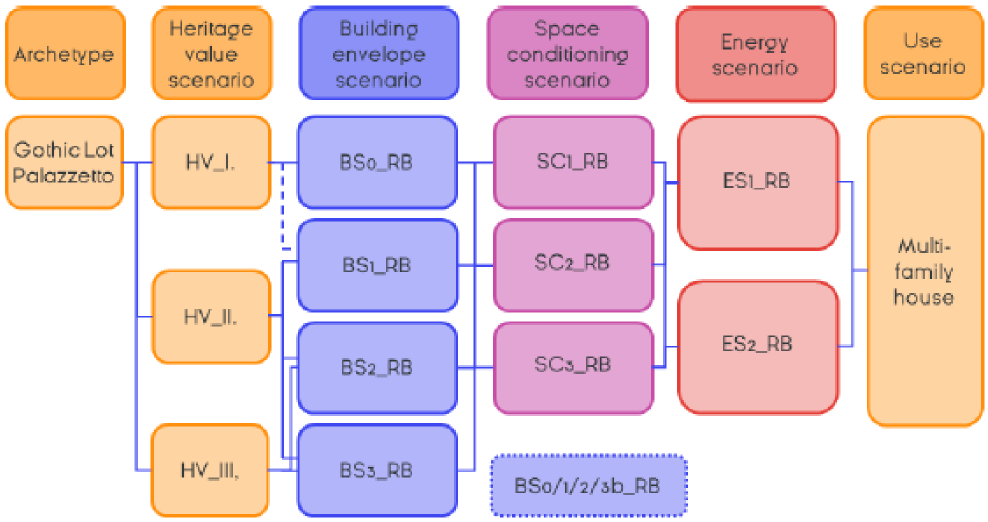


Figure 3.6 Overview of the Renovation baseline scenarios for the Palazzetto archetype

The operational information has been implemented into the model to reflect the standard use of the building typologies, as described in section 4.1.1. As far as the generation system is concerned, there is a centralized gas boiler, which produces both domestic hot water and heating. In the following tables are reported the U value for each building component, the ACH due to infiltration and the overall efficiencies of the technical systems (η_{sys}) for the Palazzetto archetype analysed.

	Pre-Renovation				Renovation					
	Pre-re, HV-I, BS1_PB	Pre-re, HV-II, BS2.1_PB	Pre-re, HV-II, BS2.2_PB	Pre-re, HV-III, BS3_PB	Re, HV-I, Bs0_RB	Re, HV-I, Bs1_RB	Re, HV-II, Bs1_RB	Re, HV-II, BS2_RB	Re, HV-II, Bs3_RB	Re, HV-III, Bs3_RB
U-Value [W/m²K]										
Exterior wall	1.81	1.81	1.81	1.81	1.81	1.81	1.81	0.63-1.81	0.39-1.56	0.39-1.56
Internal wall	2.49	2.49	2.49	2.49	2.49	2.49	2.49	2.49	2.49	2.49
Ground floor	1.75	1.75	1.75	0.61	0.28	0.28	0.28	0.28	0.28	0.28
Interior floor	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94
Attic floor	2.01	2.01	2.01	2.01	0.27	0.27	0.27	0.27	0.27	0.27
Roof	1.93	1.93	1.93	0.65	1.93	1.93	1.93	1.93	1.93	0.65
Windows	5.7	2.9-5.7	2.9	2.9	5.7	1.4	1.4	1.4	1.4	1.4
Air Change Rate [h^{-1}]										
ACH	7.5	6	4.5	4.5	4.5	3	3	3	3	3
Overall efficiency of technical systems										
$\eta_{sys, heating}$	0.73	0.73	0.73	0.73	0.89	0.89	0.89	0.89	0.89	0.89
$\eta_{sys, cooling}$	-	-	-	-	2.23	2.23	2.23	2.23	2.23	2.23

Table 3.3 Main information on U-value, Air change Rate for infiltration and overall efficiency of the technical systems adopted in the different Pre-renovation and Renovation baseline scenarios for the Palazzetto Archetype

Following the estimation of the main output related to energy, comfort and IAQ aspects for each baseline scenario are presented.

Energy Need

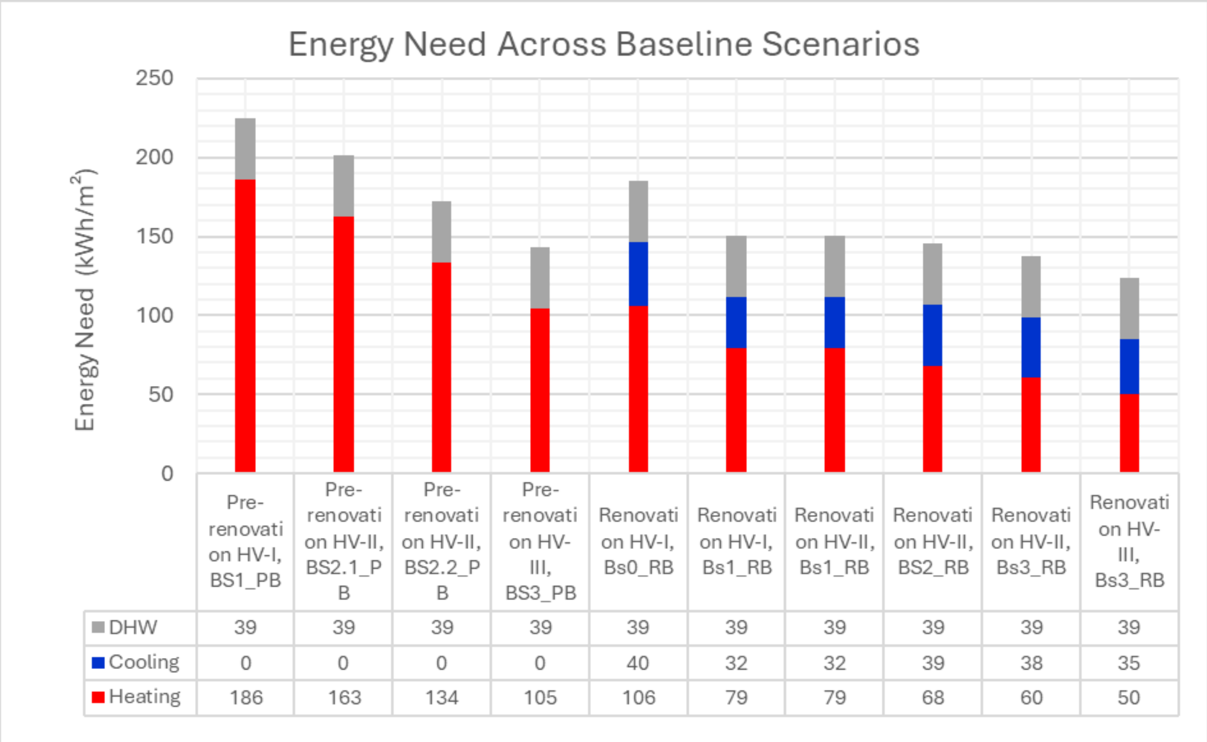
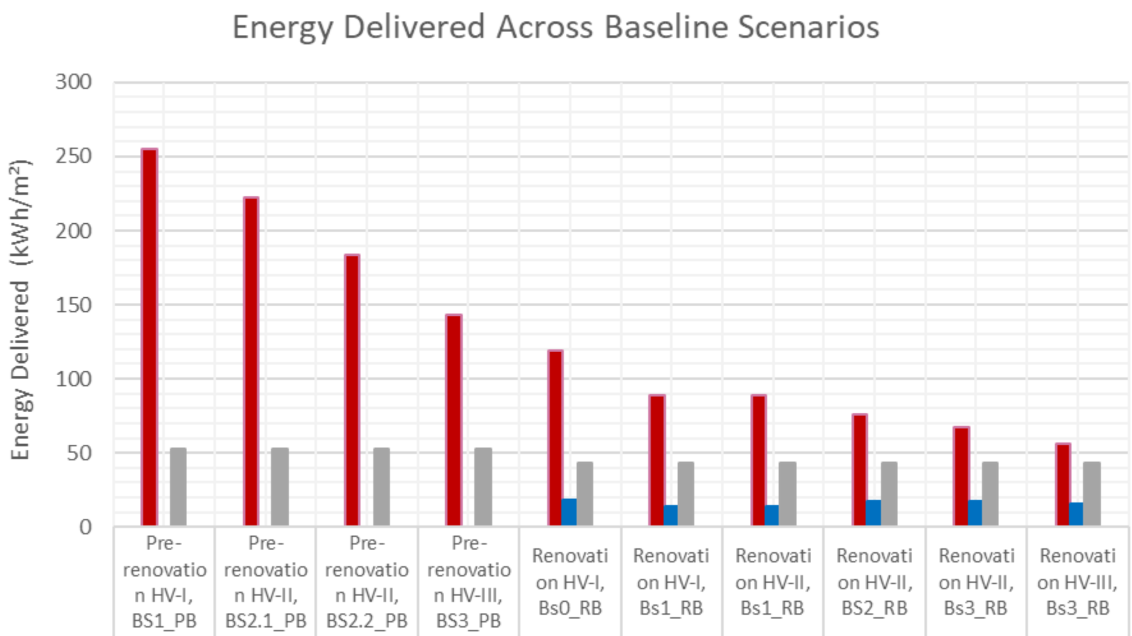


Figure 3.7 Comparison of Energy Need (heating, cooling, and DHW) results for all baseline scenarios

The graph shows how heating need is significantly reduced across renovation scenarios, while cooling demand only appears once systems are added. The best result is achieved in scenario renovation HV-II, Bs3_RB, where heating demand drops by nearly 63% compared to the specific pre-renovation baseline HV-II, Bs2.1_PB, with the lowest cooling demand as well. Domestic hot water demand remains the same in all scenarios because it is not affected by the building envelope or HVAC system upgrades. This result is mainly due to the insulation of both the horizontal and vertical envelope, the replacement of existing windows with double glazing and the reduction of air infiltration. Conversely, in the most conservative scenario HV-I, Bs0_RB, the maximum possible reduction is approximately 43% compared to the pre-retrofit baseline HV-I, Bs1_PB. This result is due to the poor thermal insulation of the building envelope, where only the floor against the ground and the ceiling towards the attic are insulated, in addition to the repair of existing windows (with a reduction in air infiltration).

Energy Delivered

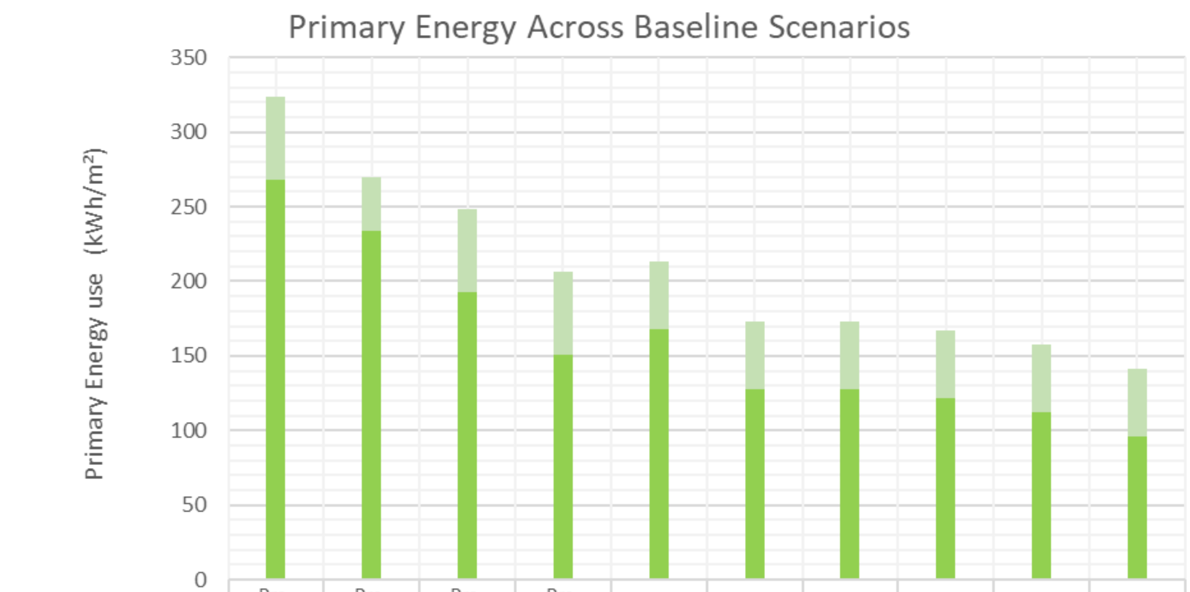


	Pre-renovation HV-I, BS1_PB	Pre-renovation HV-II, BS2.1_PB	Pre-renovation HV-II, BS2.2_PB	Pre-renovation HV-III, BS3_PB	Renovation HV-I, Bs0_RB	Renovation HV-I, Bs1_RB	Renovation HV-II, Bs1_RB	Renovation HV-II, BS2_RB	Renovation HV-II, Bs3_RB	Renovation HV-III, Bs3_RB
Heating	255	223	183	143	119	89	89	76	68	56
Cooling	0	0	0	0	18	14	14	17	17	15
DHW	53	53	53	53	43	43	43	43	43	43

Figure 3.8 Comparison of Energy Delivered (heating, cooling, and DHW) results for all baseline scenarios. It should be noted that Energy Delivered for heating and DHW refers to thermal energy, while that for cooling refers to electrical energy

This graph highlights how heating energy delivered decreases after renovation, especially in advanced scenarios. Similarly to the results obtained for energy need, the most efficient outcome is again in renovation HV-II, Bs3_RB, which lead a reduction of about 70% compared to the pre-renovation baseline HV-II, Bs2.1_PB, which combines the lowest heating need with limited cooling requirements. Conversely, in the most conservative scenario HV-I, Bs1_RB, the maximum possible reduction is approximately 65% compared to the pre-retrofit baseline HV-I, Bs1_PB.

Primary Energy Use

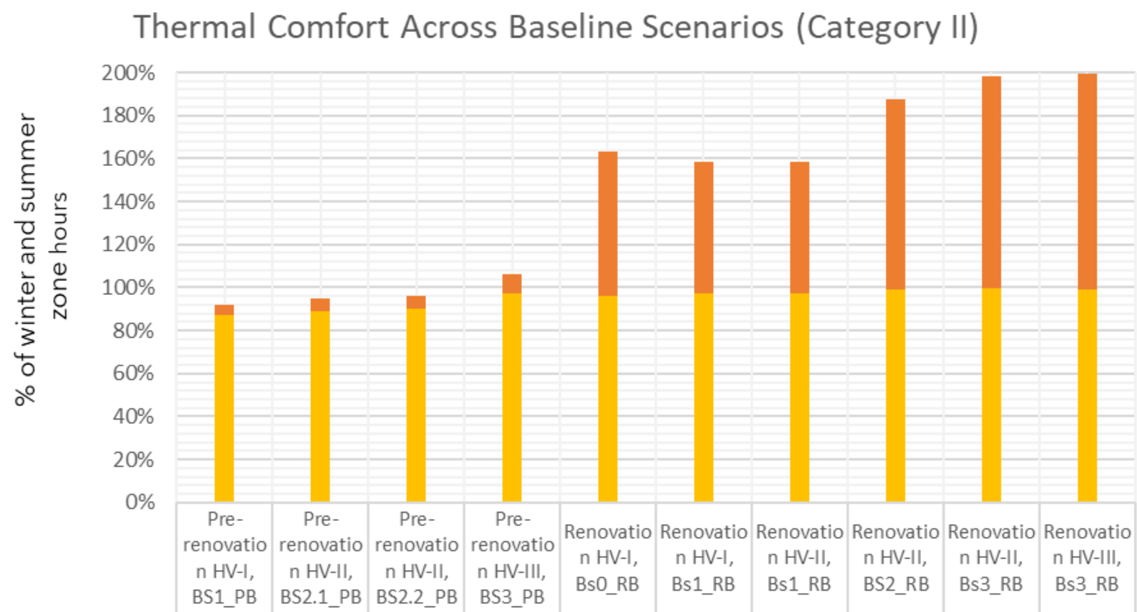


	Pre-renovation HV-I, BS1_PB	Pre-renovation HV-II, BS2.1_PB	Pre-renovation HV-II, BS2.2_PB	Pre-renovation HV-III, BS3_PB	Renovation HV-I, Bs0_RB	Renovation HV-I, Bs1_RB	Renovation HV-II, Bs1_RB	Renovation HV-II, BS2_RB	Renovation HV-II, Bs3_RB	Renovation HV-III, Bs3_RB
DHW	56	36	56	56	45	45	45	45	45	45
heating and cooling	268	234	192	151	168	128	128	122	112	96
Energy saving %					34%	46%	30%	38%	36%	31%

Figure 3.9 Comparison of Primary Energy (heating/cooling and DHW) results for all baseline scenarios. The percentage indicates the reduction in primary energy compared to the related pre-renovation scenario.

The graph shows a clear reduction in primary energy use as renovation measures and system improvements are introduced. Pre-renovation scenarios have the highest primary energy demand, dominated by heating and cooling PEU, while domestic hot water remains constant across all cases. Once high-efficiency systems are implemented, primary energy consumption decreases significantly, reaching the lowest value in scenario renovation HV-III, Bs3, which provide a reduction with respect of the pre-renovation baseline equal to the 31%. However, the scenario that results in the greatest reduction in primary energy is HV-I, Bs1_RB, which achieves a 46% reduction compared to the pre-renovation baseline HV-I, Bs1_PB.

Thermal Comfort

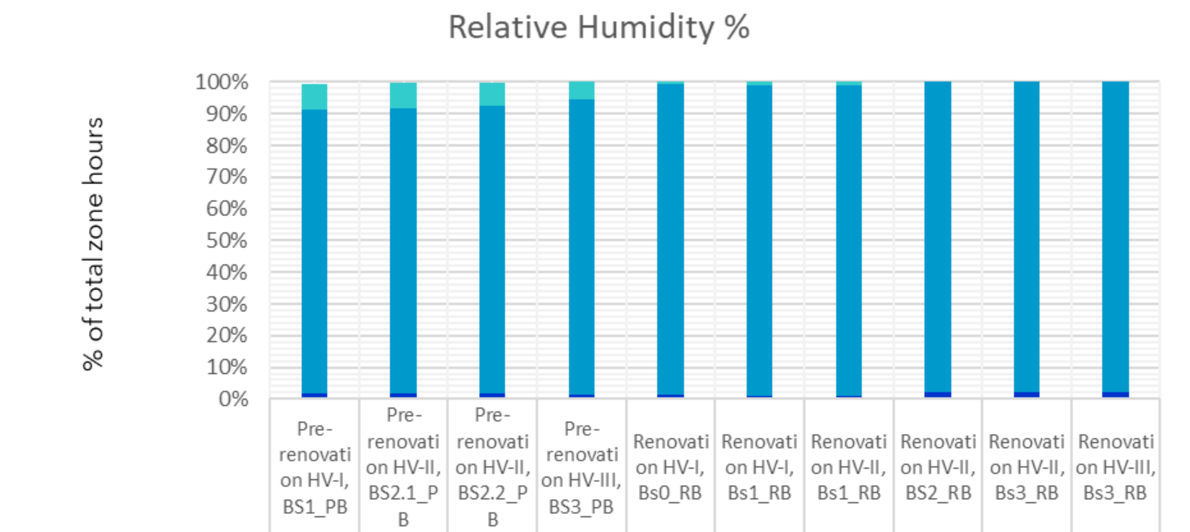


	Pre-renovation HV-I, BS1_PB	Pre-renovation HV-II, BS2.1_PB	Pre-renovation HV-II, BS2.2_PB	Pre-renovation HV-III, BS3_PB	Renovation HV-I, Bs0_RB	Renovation HV-I, Bs1_RB	Renovation HV-II, Bs1_RB	Renovation HV-II, BS2_RB	Renovation HV-II, Bs3_RB	Renovation HV-III, Bs3_RB
Winter period - h	4522	4788	5415	7562	56259	50559	50559	73853	82859	83448
Summer period - h	36917	37297	35986	40679	40375	40907	40907	41439	41724	41572
Winter period %	5%	6%	6%	9%	67%	61%	61%	89%	99%	100%
Summer period %	87%	89%	90%	97%	96%	98%	98%	99%	100%	99%

Figure 3.10 Comparison of Thermal Comfort (number of hours and % of time for winter and summer period inside CATII) results for all baseline scenarios

The figure presents the number of hours within Category II thermal comfort limits for each baseline scenario, before and after renovation. Higher values indicate better comfort performance, as a greater share of occupied hours remains within the acceptable range defined by EN 16798-1. Before renovation, all cases perform well in summer, with 87–90% of the hours meeting comfort criteria, while winter comfort is very low at only 5–9%. This is mainly due to poor insulation of both the opaque and transparent casing, which lowers the operating temperature. After renovation, summer comfort stays high in all scenarios (96–99%), meaning the building maintains good comfort during warm months. Winter comfort, however, changes much more: some scenarios still remain low (around 61%), while others show major improvements. The best result is in renovation HV-III, Bs3, where winter comfort reaches 100%, meaning the full winter period meets the Category II limits. This is mainly due to improved insulation of the building envelope, especially the external walls.

Relative Humidity



	Pre-renovation HV-I, BS1_PB	Pre-renovation HV-II, BS2.1_PB	Pre-renovation HV-II, BS2.2_PB	Pre-renovation HV-III, BS3_PB	Renovation HV-I, Bs0_RB	Renovation HV-I, Bs1_RB	Renovation HV-II, Bs1_RB	Renovation HV-II, BS2_RB	Renovation HV-II, Bs3_RB	Renovation HV-III, Bs3_RB
Above 70%	8%	8%	7%	6%	1%	1%	1%	0%	0%	0%
Between 30% & 70%	90%	90%	91%	93%	98%	98%	98%	98%	98%	98%
Below 30%	2%	2%	2%	1%	1%	1%	1%	2%	2%	2%
Above 70% - h	14326	13319	12255	10070	1349	931	931	665	418	399
Between 30% & 70% - h	149169	150233	151449	153919	162792	150613	150613	163153	162564	162716
Below 30% -h	2945	2888	2736	2451	2299	14896	14896	2622	3458	3325

Figure 3.11 Comparison of Relative Humidity results for all baseline scenarios. The graph shows the number of hours and % of time inside the optimal range for RH (30-70%), below 30% of RH and above 70% of RH

The graph shows the number of hours during which relative humidity (RH) fell below 30%, between 30–70%, and above 70%, across different periods. Most hours fall within the 30–70% range, indicating that indoor humidity is generally maintained within the recommended level, with percentages ranging from 75% to 91% (highest in HV-III, Bs3). Very low humidity (<30%) is rare, about 2% of total hours. High humidity (>70%) decreased after renovations, from 6%-8% pre-renovation to 0-1 % post-renovation, showing improved humidity control. Overall, the building's humidity is mostly within the ideal range, and renovations and HVAC adjustments effectively reduced excessive humidity while very dry conditions remain uncommon.

CO_2 Concentration

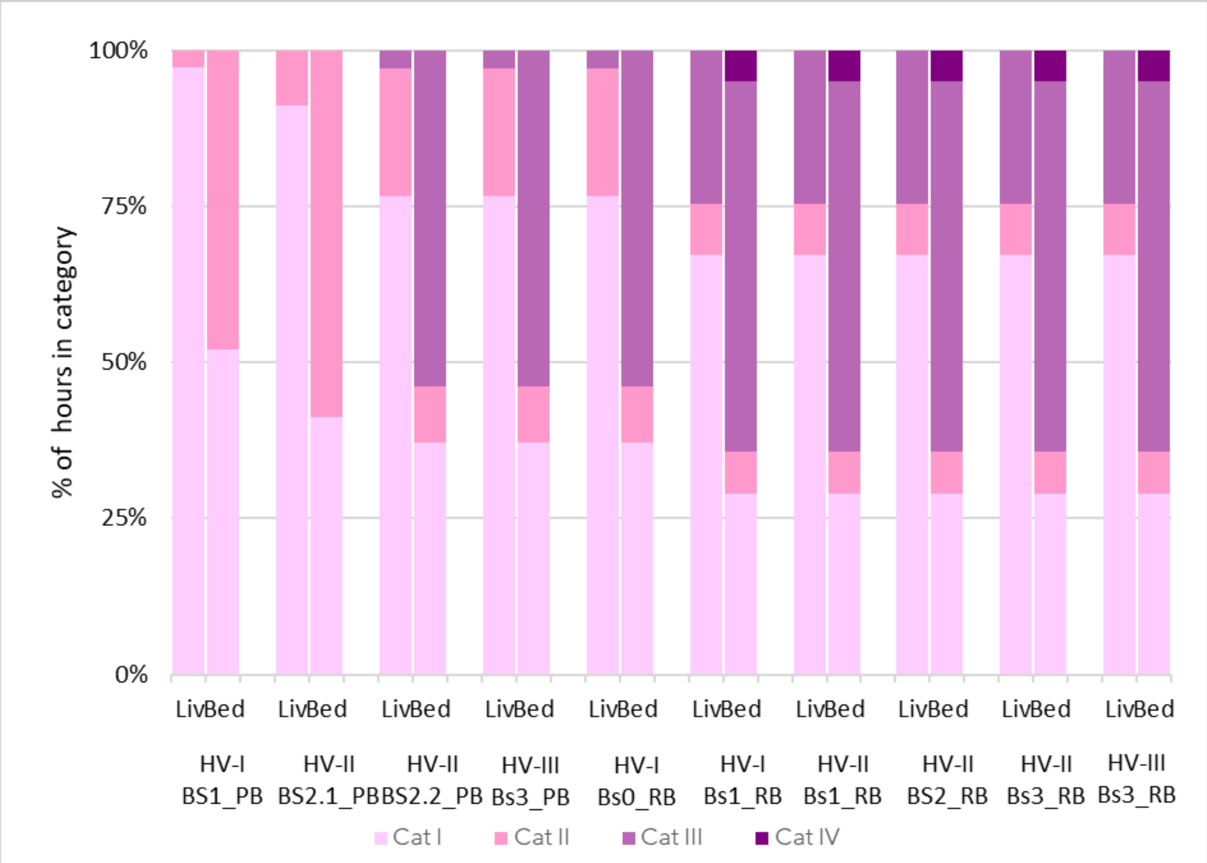


Figure 3.12 Comparison of CO2 concentration results for all baseline scenarios for the living room and the bedroom (Occ_A). The graph shows the percentage of time for each category: CAT II includes CAT I, CAT III includes CAT I and II, and CAT IV encompasses all prior categories.

The results are obtained based on different ACH values for each scenario, meaning that the pre-renovation scenario shows the highest ACH values, and as interventions increase, the ACH values decrease. According to the results shown in the figure above, the values for the CO_2 concentration for the living room are mostly in CAT I throughout a year, though some are present in CAT II and CAT III. In the first pre-renovation scenario, up to 97% of hours are in CAT I and 3% in CAT II. For the final post-renovation scenario, with a lowered ACH, the CO_2 concentrations are distributed as follows: annual hours in CAT I, 67%; above CAT I within CAT II, 8%; and up to the threshold of CAT III, 25%. Meanwhile, the CO_2 concentration values for the bedroom in the first pre-renovation scenario is 52% within CAT I and the remaining 48% within CAT II. In the final post-renovation scenario, this distribution changes to 29% within CAT I, 7% between CAT I and CAT II, 59% in the zone between CAT II and CAT III, and the remaining 5% of hours within the CAT IV. This issue will need to be adequately addressed in more advanced renovation scenarios, which may involve the implementation of more effective natural ventilation strategies or the installation of mechanical ventilation systems.

3.1.3. Gothic lot

The most common building archetype at neighbourhood scale in Mantua is the Gothic lot, a typical medieval townhouse with a narrow street-facing facade and greater depth, often featuring three floors and a rear courtyard used for hygiene and domestic activities. Its layout is functional, with stairs positioned either centrally or along the length, and includes light wells to improve natural lighting. In both the pre-renovation and renovation baseline scenarios, the entire building is considered heated and occupied, except for the attic and cellar. As described above, each floor is considered occupied by a family of four. Furthermore, no changes to the spatial layout are expected in the renovation baseline. The main simulations carried out are described below.

Pre-renovation (as is)

The case study involves a historical building located in Mantua, indicated as "Occ_B". The building dates back to the 18th–19th centuries, with some floor reconstructions completed during the 20th century. It covers a surface area of 394 m² and has remained unoccupied for the past decade. The structure is a masonry building with wooden floors and is classified under a Gothic lot typology. It is subject to indirect heritage protection regulations (Art. 45 L.42/2004, PGT Art. D16 - A3), being located in an area contiguous to the UNESCO site.

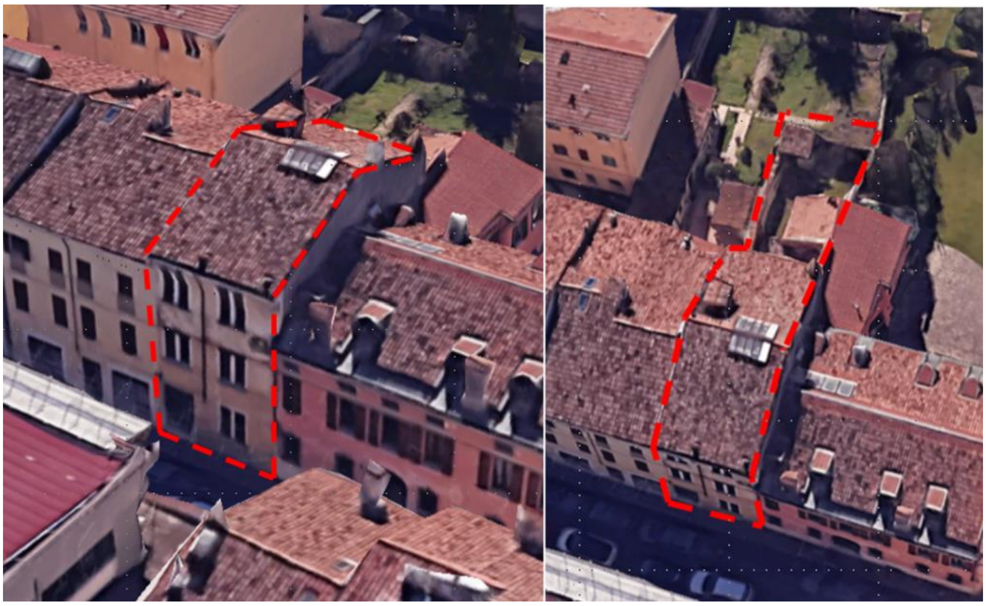


Figure 3.13 View of the Occ_B case study

In detail, the model of the building under study is composed of 24 thermal zones, subdivided according to the different uses foreseen in the design state. A view of the realised energy model is presented below.

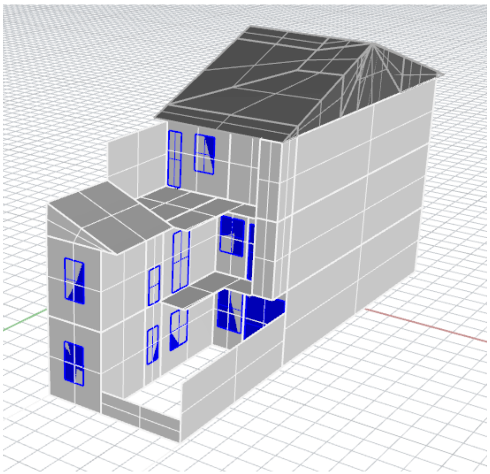


Figure 3.14 Comparison View of the digital energy model of the building

The building was segmented (in the BES model) into individual floors and further divided into thermal zones, hereafter reported.

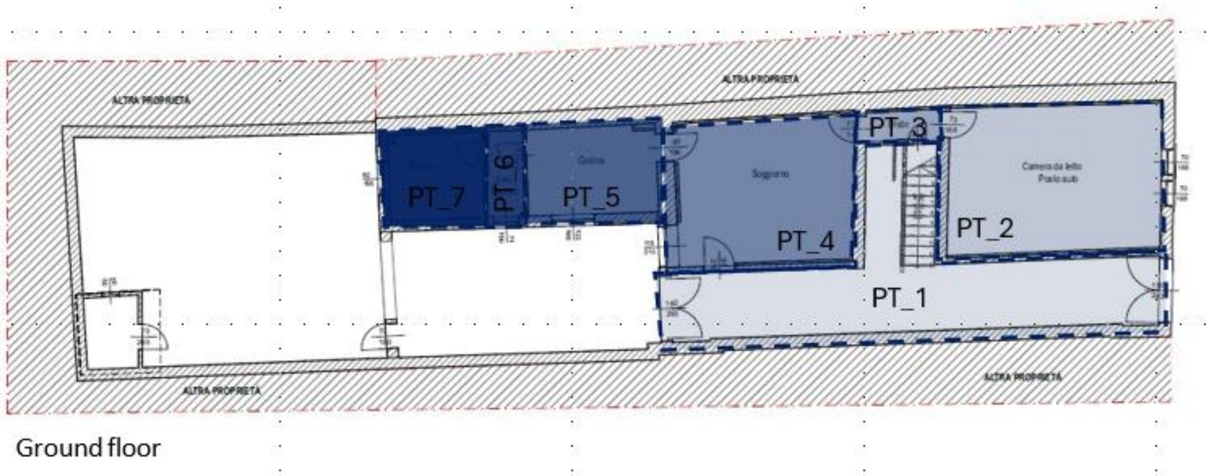


Figure 3.15 Comparison Detail of thermal zones with our nomenclature

Space	Number of thermal zones	Code
Ground floor	7 zones	PT_1 to PT_7
First floor	8 zones	PP_1 to PP_8
Second floor	7 zones	SP_1 to SP_7
Attic	5 zones	ST_1 to ST_5

Table 3.4 Detail of thermal zones with our nomenclature

Due to limited archival data. construction layers were hypothesized based on historical context. material types. and typical construction practices. Multiple wall types (0.1–0.5 m thick). floors. and roof assemblies were defined. with respective thermal properties (conductivity. density. specific heat). Windows were assumed to be single glazed with timber frames. having a transmittance of 5.7 W/m²K. The simulation has been carried out considering the weather data collected in Mantua in the same year of the internal monitoring.

The original wall structure is in plastered brick load-bearing masonry. In the wall texture it is possible to see the presence of raw bricks. The newest part of the building, built in the 50s and corresponding to the portion of the ground floor and first floor facing the internal courtyard, has been made with concrete slabs and brick walls. Brickwork in raw bricks from 18th century; brickwork with cooked brick in the 50s wing. Since the building was unoccupied, the following data have been adopted as profile. On these bases, the model calibration and validation has been performed according to the methodology above mentioned in the previous chapter, comparing the RH and T of the different acquired data with the ones resulting from the simulation. Adopting such process a RMSE lower than 2°C for temperature has been obtained with the parameters previously described.

Results for Pre-renovation and Renovation baseline scenario

According to D5.4, the Pre-renovation baseline scenarios defined for the Gothic lot archetype are shown in the scheme below.

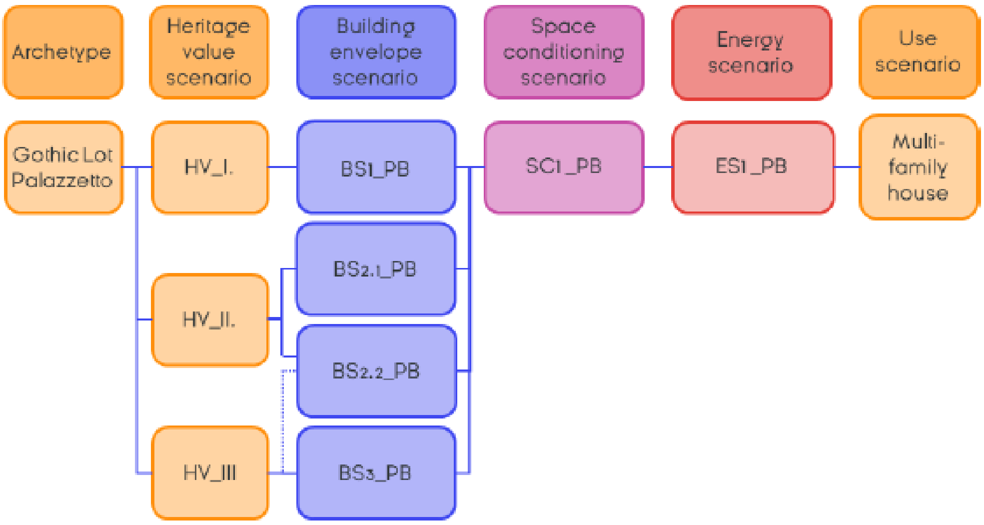


Figure 3.16 Overview of the Pre-renovation baseline scenarios for the Gothic lot archetype.

Similarly, based on D5.4, the Renovation baseline scenarios defined for the Gothic lot archetype are shown in the scheme below.

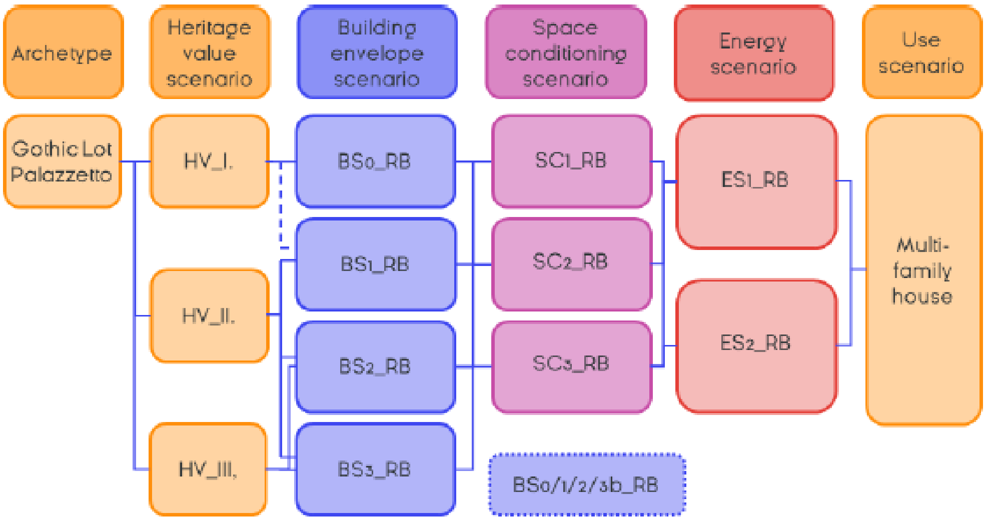


Figure 3.17 Overview of the Renovation baseline scenarios for the Gothic lot archetype.

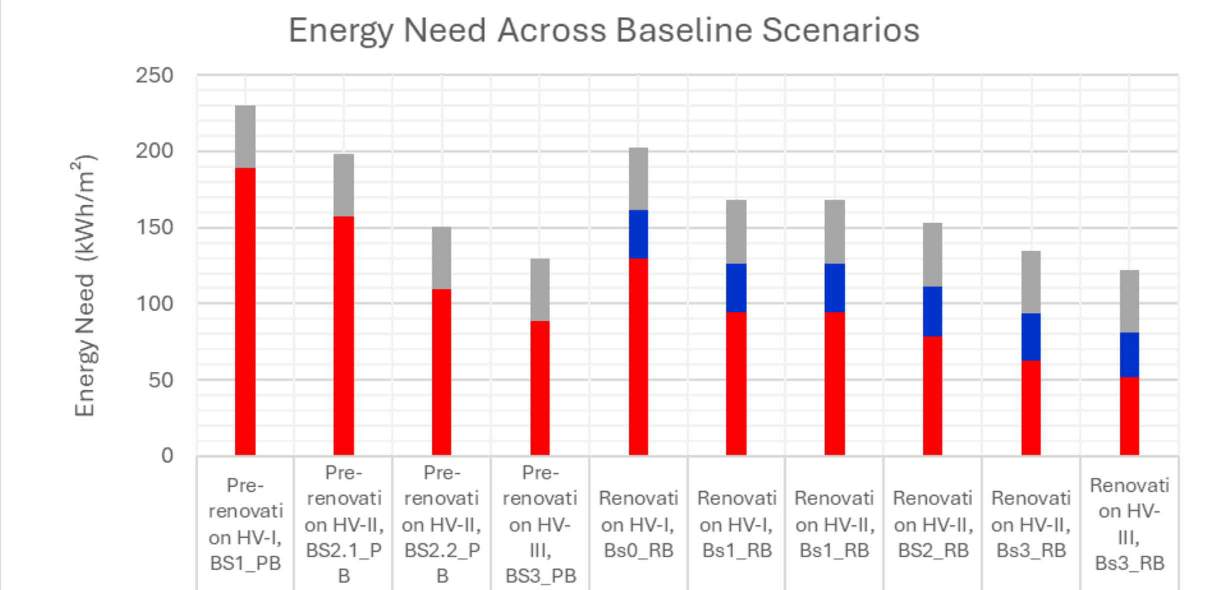
The operational information have been implemented into the model to reflect the standard use of the building typologies, as described in section 4.1.1. As far as the generation system is concerned, there is a centralized gas boiler, which produces both domestic hot water and heating. In the following tables are reported the U value for each building component, the ACH due to infiltration and the overall efficiencies of the technical systems (η_{sys}) for Gothic lot archetype analysed.

	Pre-renovation				Renovation					
	Pre-re, HV-I, BS1_PB	Pre-re, HV-II, BS2.1_PB	Pre-re, HV-II, BS2.2_PB	Pre-re, HV-III, BS3_PB	Re, HV-I, Bs0_RB	Re, HV-I, Bs1_RB	Re, HV-II, Bs1_RB	Re, HV-II, BS2_RB	Re, HV-II, Bs3_RB	Re, HV-III, Bs3_RB
U-Value [W/m²K]										
Exterior wall	0.96-1.56	0.96-1.56	0.96-1.56	0.96-1.56	0.96-1.56	0.96-1.56	0.96-1.56	0.96-1.56	0.28	0.28
Internal wall	0.96-1.42-2.49	0.96-1.42-2.49	0.96-1.42-2.49	0.96-1.42-2.49	0.96-1.42-2.49	0.96-1.42-2.49	0.96-1.42-2.49	0.96-1.42-2.49	0.96-1.42-2.49	0.96-1.42-2.49
Ground floor	1.75	1.75	1.75	0.61	0.28	0.28	0.28	0.28	0.28	0.28
Interior floor	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94
Attic floor	2.01	2.01	2.01	2.01	0.27	0.27	0.27	0.27	0.27	0.27
Roof	1.93	1.93	1.93	0.65	1.93	1.93	1.93	1.93	1.93	0.65
Windows	5.7	2.9	2.9	2.9	5.7	1.4	1.4	1.4	1.4	1.4
Air Change Rate [h^{-1}]										
ACH	7.5	6	4.5	4.5	4.5	3	3	3	3	3
Overall efficiency of technical systems										
$\eta_{sys, heating}$	0.73	0.73	0.73	0.73	0.89	0.89	0.89	0.89	0.89	0.89
$\eta_{sys, cooling}$	-	-	-	-	2.23	2.23	2.23	2.23	2.23	2.23

Table 3.5 Main information on U-value, Air change Rate for infiltration and overall efficiency of the technical systems adopted in the different Pre-renovation and Renovation baseline scenarios for the Gothic lot Archetype.

Following the estimation of the main output related to energy, comfort and IAQ aspects for each baseline scenario are presented.

Energy Need

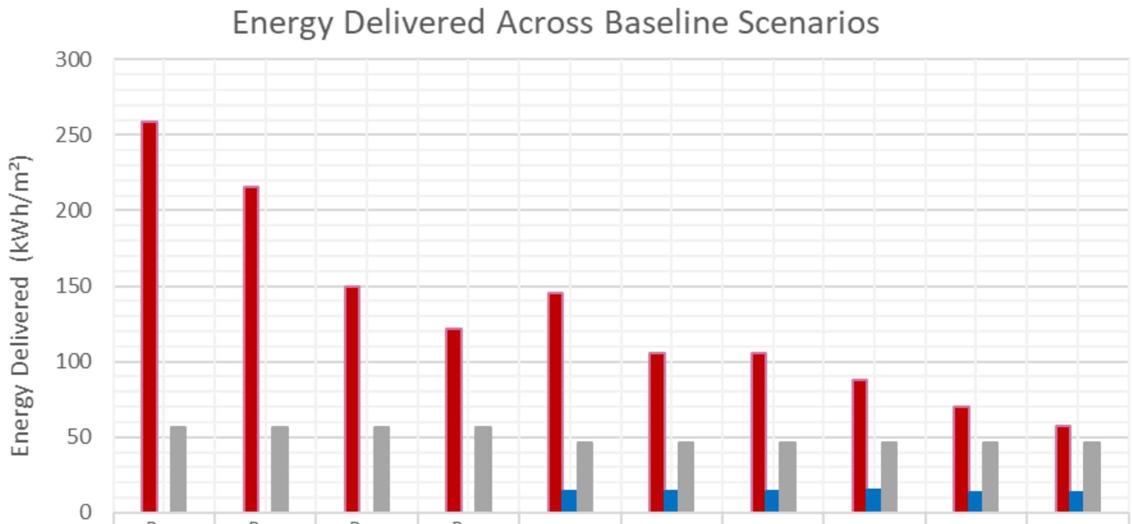


	Pre-renovation HV-I, BS1_PB	Pre-renovation HV-II, BS2.1_PB	Pre-renovation HV-II, BS2.2_PB	Pre-renovation HV-III, BS3_PB	Renovation HV-I, Bs0_RB	Renovation HV-I, Bs1_RB	Renovation HV-II, Bs1_RB	Renovation HV-II, BS2_RB	Renovation HV-II, Bs3_RB	Renovation HV-III, Bs3_RB
DHW	41	41	41	41	41	41	41	41	41	41
Cooling	0	0	0	0	31	32	32	33	31	30
Heating	189	157	109	89	130	95	95	78	63	51

Figure 3.18 Comparison of Energy Need (heating, cooling, and DHW) results for all baseline scenarios.

The graph shows how heating need is significantly reduced across renovation scenarios, while cooling demand only appears once systems are added. The best result is achieved in scenario renovation HV-II, Bs3_RB, where heating demand drops by nearly 60% compared to the specific pre-renovation baseline HV-II, Bs2.1_PB, with the lowest cooling demand as well. Domestic hot water demand remains the same in all scenarios because it is not affected by the building envelope or HVAC system upgrades. This result is mainly due to the insulation of both the horizontal and vertical envelope, the replacement of existing windows with double glazing and the reduction of air infiltration. Conversely, in the most conservative scenario HV-I, Bs0_RB, the maximum possible reduction is approximately 31% compared to the pre-retrofit baseline HV-I, Bs1_PB. This result is due to the poor thermal insulation of the building envelope, where only the floor against the ground and the ceiling towards the attic are insulated, in addition to the repair of existing windows (with a reduction in air infiltration).

Energy Delivered

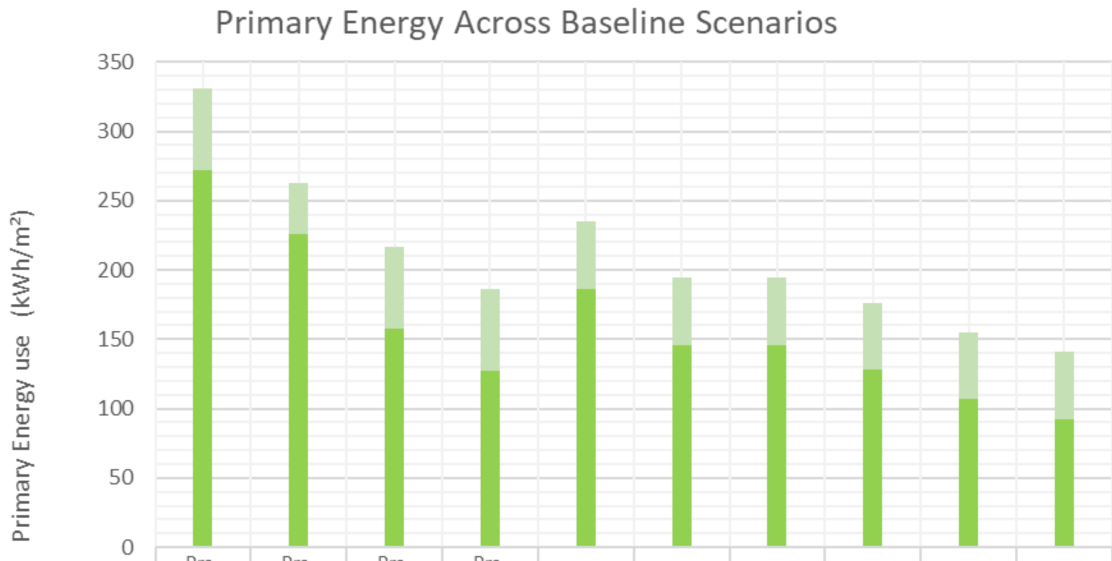


	Pre-renovation HV-I, BS1_PB	Pre-renovation HV-II, BS2.1_PB	Pre-renovation HV-II, BS2.2_PB	Pre-renovation HV-III, BS3_PB	Renovation HV-I, Bs0_RB	Renovation HV-I, Bs1_RB	Renovation HV-II, Bs1_RB	Renovation HV-II, BS2_RB	Renovation HV-II, Bs3_RB	Renovation HV-III, Bs3_RB
Heating	259	216	150	121	145	106	106	88	70	58
Cooling	0	0	0	0	14	14	14	15	14	13
DHW	56	56	56	56	46	46	46	46	46	46

Figure 3.19 Comparison of Energy Delivered (heating, cooling, and DHW) results for all baseline scenarios. It should be noted that Energy Delivered for heating and DHW refers to thermal energy, while that for cooling refers to electrical energy.

This graph highlights how heating energy delivered decreases after renovation, especially in advanced scenarios. Similarly to the results obtained for energy need, the most efficient outcome is again in renovation HV-II, Bs3_RB, which lead a reduction of about 68% compared to the pre-renovation baseline HV-II, Bs2.1_PB, which combines the lowest heating need with limited cooling requirements. Conversely, in the most conservative scenario HV-I, Bs1_RB, the maximum possible reduction is approximately 59% compared to the pre-retrofit baseline HV-I, Bs1_PB.

Primary Energy Use

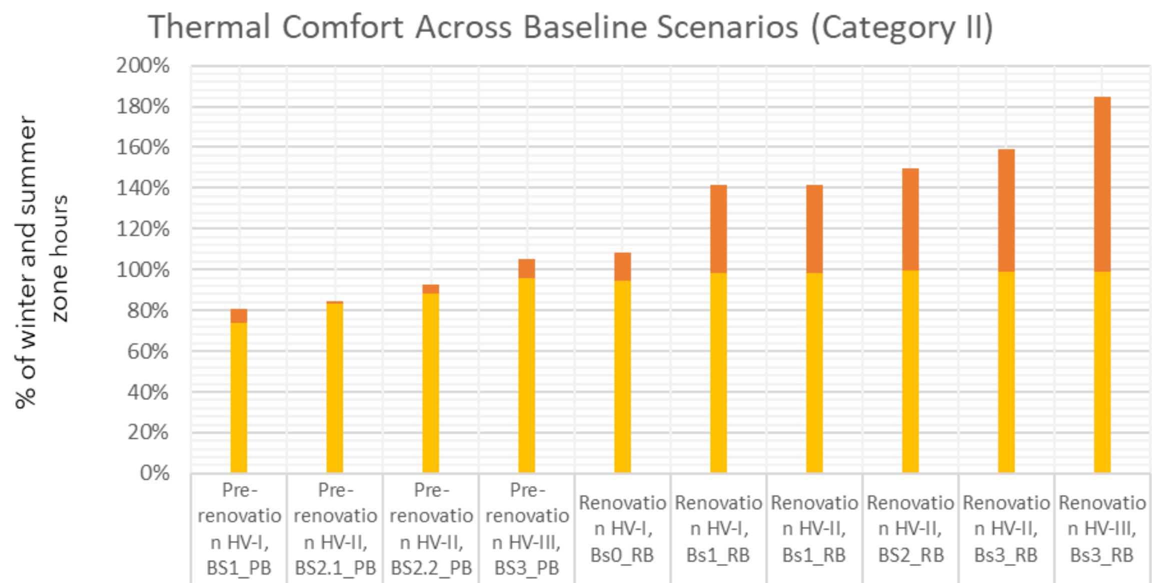


	Pre-renovation HV-I, BS1_PB	Pre-renovation HV-II, BS2.1_PB	Pre-renovation HV-II, BS2.2_PB	Pre-renovation HV-III, BS3_PB	Renovation HV-I, Bs0_RB	Renovation HV-I, Bs1_RB	Renovation HV-II, Bs1_RB	Renovation HV-II, BS2_RB	Renovation HV-II, Bs3_RB	Renovation HV-III, Bs3_RB
DHW	59	36	59	59	48	48	48	48	48	48
heating and cooling	272	226	157	128	187	146	146	128	107	92
Energy saving %					29%	41%	10%	33%	28%	25%

Figure 3.20 Comparison of Primary Energy (heating/cooling and DHW) results for all baseline scenarios. The percentage indicates the reduction in primary energy compared to the related pre-renovation scenario.

The graph shows a clear reduction in primary energy use as renovation measures and system improvements are introduced. Pre-renovation scenarios have the highest primary energy demand, dominated by heating and cooling PEU, while domestic hot water remains constant across all cases. Once high-efficiency systems are implemented, primary energy consumption decreases significantly, reaching the lowest value in scenario renovation HV-III, Bs3, which provide a reduction with respect of the pre-renovation baseline equal to the 25%. However, the scenario that results in the greatest reduction in primary energy is HV-I, Bs1_RB, which achieves a 41% reduction compared to the pre-renovation baseline HV-I, Bs1_PB.

Thermal Comfort

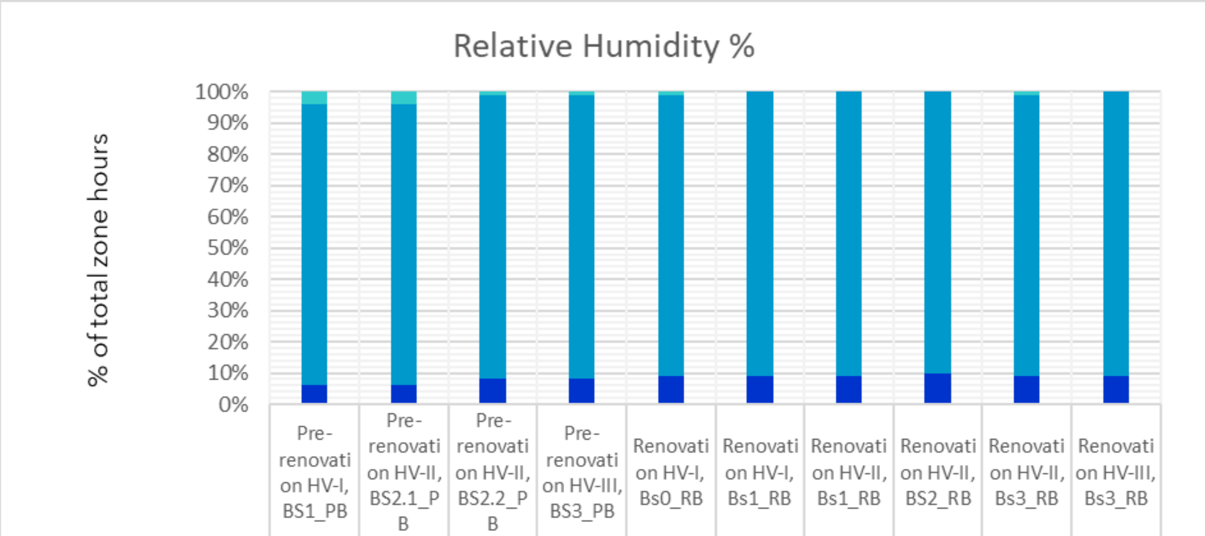


	Pre-renovation HV-I, BS1_PB	Pre-renovation HV-II, BS2.1_PB	Pre-renovation HV-II, BS2.2_PB	Pre-renovation HV-III, BS3_PB	Renovation HV-I, Bs0_RB	Renovation HV-I, Bs1_RB	Renovation HV-II, Bs1_RB	Renovation HV-II, BS2_RB	Renovation HV-II, Bs3_RB	Renovation HV-III, Bs3_RB
Winter period - h	5643	855	3154	7885	11438	35986	35986	41971	49742	72124
Summer period - h	30970	34998	37126	40223	39558	41325	41325	41610	41477	41420
Winter period %	7%	1%	4%	9%	14%	43%	43%	50%	60%	86%
Summer period %	74%	83%	89%	96%	94%	99%	99%	99%	99%	99%

Figure 3.21 Comparison of Thermal Comfort (number of hours and % of time for winter and summer period inside CATII) results for all baseline scenarios.

The figure presents the number of hours within Category II thermal comfort limits for each baseline scenario, before and after renovation. Higher values indicate better comfort performance, as a greater share of occupied hours remains within the acceptable range defined by EN 16798-1. Before renovation, all cases perform well in summer, with 74–96% of the hours meeting comfort criteria, while winter comfort is very low at only 1–9%. After renovation, summer comfort stays high in all scenarios (94–99%), meaning the building maintains good comfort during warm months. Winter comfort, however, changes much more: some scenarios remain low (around 14%), while others show major improvements. The best result is in renovation HV-III, Bs3, where winter comfort reaches 86%, meaning the full winter period meets the Category II limits.

Relative Humidity



	Pre-renovation on HV-I, BS1_PB	Pre-renovation on HV-II, BS2.1_PB	Pre-renovation on HV-II, BS2.2_PB	Pre-renovation on HV-III, BS3_PB	Renovation on HV-I, Bs0_RB	Renovation on HV-I, Bs1_RB	Renovation on HV-II, Bs1_RB	Renovation on HV-II, BS2_RB	Renovation on HV-II, Bs3_RB	Renovation on HV-III, Bs3_RB
Above 70%	4%	4%	1%	1%	1%	0%	0%	0%	1%	0%
Between 30% & 70%	90%	90%	91%	91%	90%	91%	91%	90%	90%	91%
Below 30%	6%	6%	8%	8%	9%	9%	9%	10%	9%	9%
Above 70% - h	7049	7353	2090	1083	1425	950	950	304	836	798
Between 30% & 70% - h	149321	149644	151506	151069	150727	150879	150879	149663	150233	150423
Below 30% - h	10070	9443	12844	14288	14288	14611	14611	16473	15371	15219

Figure 3.22 Comparison of Relative Humidity results for all baseline scenarios. The graph shows the number of hours and % of time inside the optimal range for RH (30-70%), below 30% of RH and above 70% of RH.

The graph shows the number of hours during which relative humidity (RH) fell below 30%, between 30–70%, and above 70%, across different periods. Most hours fall within the 30–70% range, indicating that indoor humidity is generally maintained within the recommended level, with percentages ranging from 90% to 91%. Very low humidity (<30%) is rare, about 6%-8% in pre-renovation and almost 9% in post-renovation scenarios. High humidity (>70%) decreased after renovations, from 1%-4% pre-renovation to 0-1% post-renovation, showing improved humidity control. Overall, the building's humidity is mostly within the ideal range, and renovations and HVAC/Bs adjustments effectively reduced excessive humidity while very dry conditions remain uncommon.

CO_2 Concentration

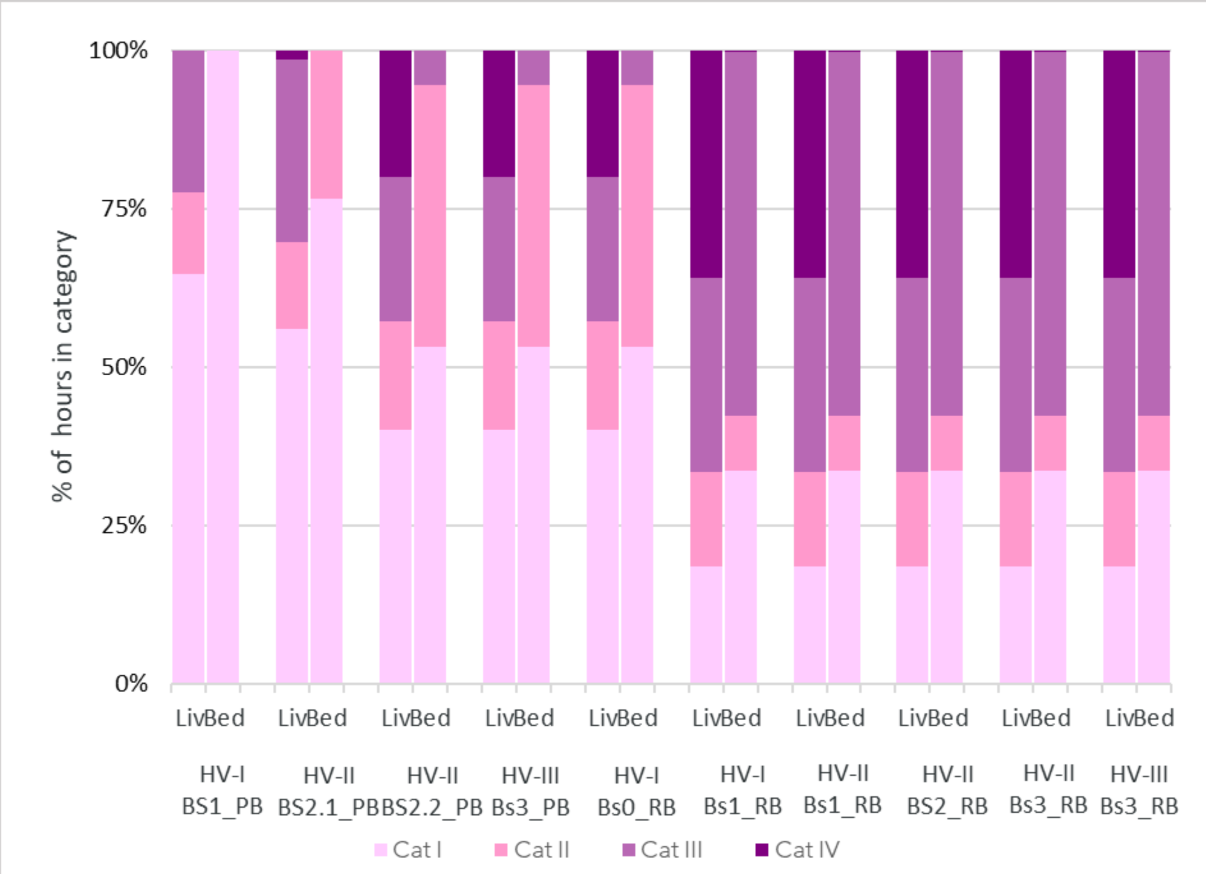


Figure 3.23 Comparison of CO2 concentration results for all baseline scenarios for the living room and the bedroom (Occ_B). The graph shows the percentage of time for each category: CAT II includes CAT I, CAT III includes CAT I and II, and CAT IV encompasses all prior categories.

According to the results shown in Figure 27, the annual distribution of CO_2 concentration levels for the living room in the initial pre-renovation scenario is 65% within CAT I, 13% above CAT I but within CAT II, and the remaining 22% within CAT III. In the final post-renovation scenario, the distribution extends up to CAT IV. For the bedroom, the CO_2 concentration in the initial pre-renovation scenario is entirely (100%) within CAT I. In the final post-renovation scenario, this changes to 34% within CAT I, 8% in the area between CAT I and CAT II, and the remaining 58% of hours in the zone between CAT II and CAT III. This issue will need to be adequately addressed in more advanced renovation scenarios, which may involve the implementation of more effective natural ventilation strategies or the installation of mechanical ventilation systems.

3.1.4. Extended building

Another building archetype is the Extended building, or houses in line. It results from merging multiple Gothic lots. These buildings have wider, often irregular facades with multiple entrances, including carriage access, and feature more symmetrical internal layouts. In both the pre-renovation and renovation baseline scenarios, the entire building is considered heated and occupied, except for the attic and cellar. As described above, each floor is considered occupied by a family of four. Furthermore, no changes to the spatial layout are expected in the renovation baseline. The main simulations carried out are described below.

Pre-renovation (as is)

The case study involves a historical residential building located in Mantua, indicated as "Occ_C". The building dates back to the early 16th century and exemplifies the extended building typology, characterized by a linear distribution of rooms and common spaces along a central corridor. It comprises two floors above ground and a non-accessible attic with a double-pitched roof and a high inter-storey space, organized with a stone staircase of architectural and historical value located at the end of the corridor. The total surface area of the building is approximately 560 m². Fragments of late 16th-century frescoes are preserved on the walls of both the ground and first floors, while the common spaces are covered by brick vaults with small window openings. The property is classified under the extended building archetype and is located within the UNESCO buffer zone of Mantua.

Figure 3.24 View of the Occ_C case study.

In detail, the energy model of the building under study consists of 23 thermal zones. These zones have been defined based on the functional distribution proposed in the design phase, with each zone representing areas that share similar usage, occupancy patterns, and thermal characteristics. This subdivision allows for a more accurate simulation of the building's energy performance. A visual representation of the completed energy model is provided below.

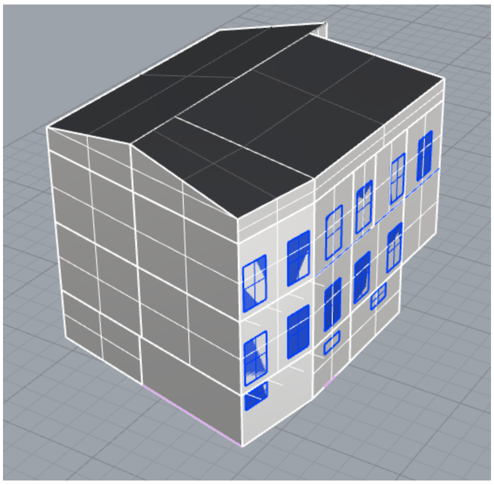


Figure 3.25 View of the digital energy model of the building.

The building was segmented (in the BES model) into individual floors and further divided into thermal zones, hereafter reported.

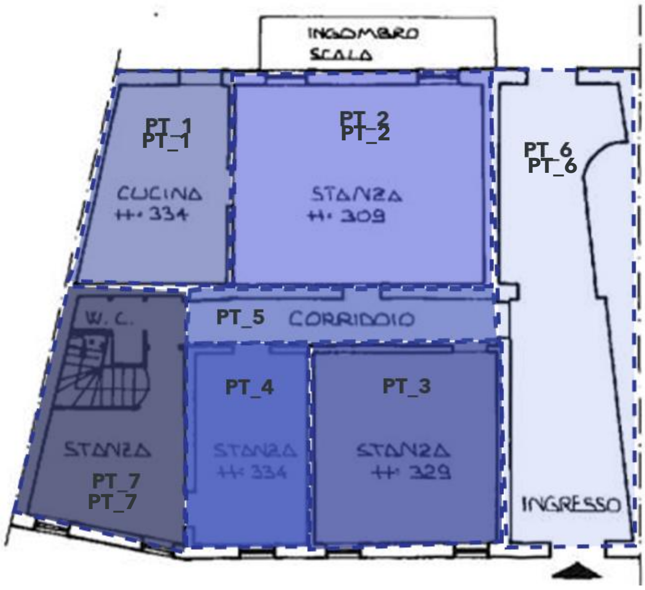


Figure 3.26 Detail of thermal zones with our nomenclature (Ground floor).

Space	Number of thermal zones	Code
Basement	5 zone	PB_1 to PB_5
Ground floor	7 zones	PT_1 to PT_7
First floor	10 zones	PP_1 to PP_10
Attic	1 zone	ST_1

Table 3.6 Detail of thermal zones with our nomenclature.

The structure is composed of plastered solid brick loadbearing masonry with exposed wooden floors. The roof is a double pitched system constructed with wooden planking, joists, and circular section beams. Due to the considerable dimensions of the attic, the roof structure is supported by brick pillars, while the ridge of the two pitches rests on the central spine wall of the building. The external roof cladding is finished with antique tiles. Almost all windows have been retrofitted with double glazing and restored shading systems, improving both thermal comfort and energy performance. Interior spaces are characterized by brick vaults, particularly in the common areas, where daylight is admitted through small window openings. The ground floor comprises a living room with a kitchen and three fulltime occupied rooms. Notably, fragments of late 16thcentury frescoes are preserved on the walls of both the ground and first floors. The attic, non-accessible and pillared, features a very high inter-story space beneath the double pitched roof, reinforcing the building's historic architectural character. The building is actually used to host young people spending period in connection with the church activities, for long or short terms – just few residents live permanently here, while some shared rooms at the second floor are thought to be used in workshop/temporary occasions. Since the building was occupied, the setpoints for heating is 20 °C. No cooling system was considered in the energy analysis.

For Case Study 3 in Mantua, the building's energy demand for 2023 was simulated and validated against monitoring data using an hourly weather file (temperature, humidity, wind, and solar radiation). Following ASHRAE Guideline 14, the Normalized Mean Bias Error (NMBE) and Coefficient of Variation of Root Mean Square Error (CVRMSE) were applied as error indicators. NMBE shows under- or overestimation tendencies, while CVRMSE reflects overall reliability.

During the initial calibration process, a significant discrepancy was observed between the energy demand estimated from utility bills and the results obtained from the Grasshopper simulations, with the billed consumption being notably higher.

Index	Result	ASHRAE Guideline 14 Threshold
NMBE	4%	±5% (Monthly)
CVRMSE	14%	15% (Monthly)

Table 3.7 Calibration results for Case Study 3 in Mantua (2023).

To enhance the model's accuracy, several adjustments were introduced while maintaining the construction materials unchanged. The most impactful modification was an increase in the heating setpoint temperature, which was originally set at 20 °C and adjusted to 22 °C IN February and March. This change better reflected the actual indoor comfort conditions of the building's occupants and contributed to reducing the gap between simulated and measured energy demand.

Results for Pre-renovation and Renovation baseline scenario

According to D5.4, the Pre-renovation baseline scenarios defined for the Extended building archetype are shown in the scheme below.

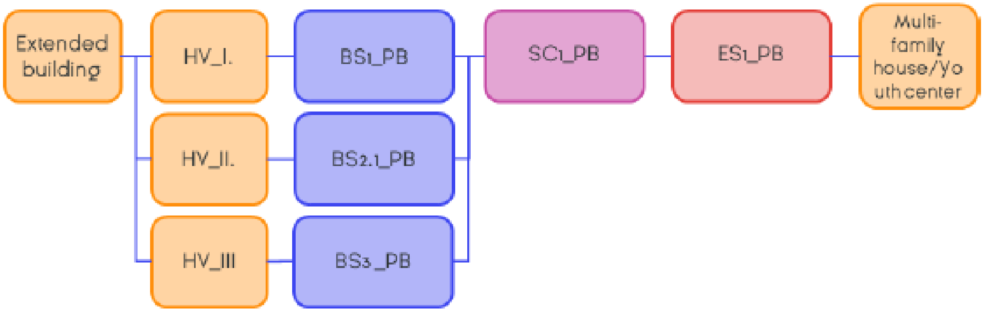


Figure 3.27 Overview of the Pre-renovation baseline scenarios for the Extended building archetype.

Similarly, based on D5.4, the Renovation baseline scenarios defined for the Extended building archetype are shown in the scheme below.

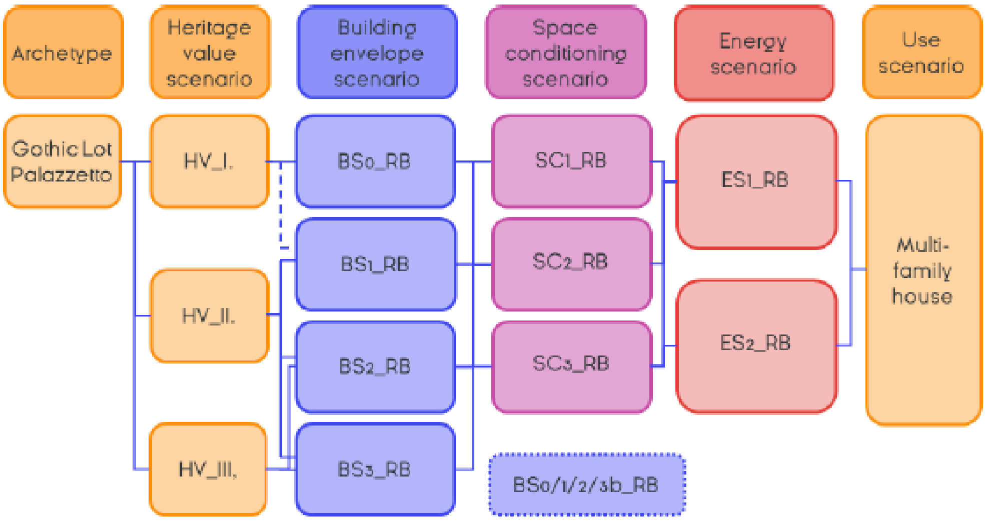


Figure 3.28 Overview of the Renovation baseline scenarios for the Extended building archetype.

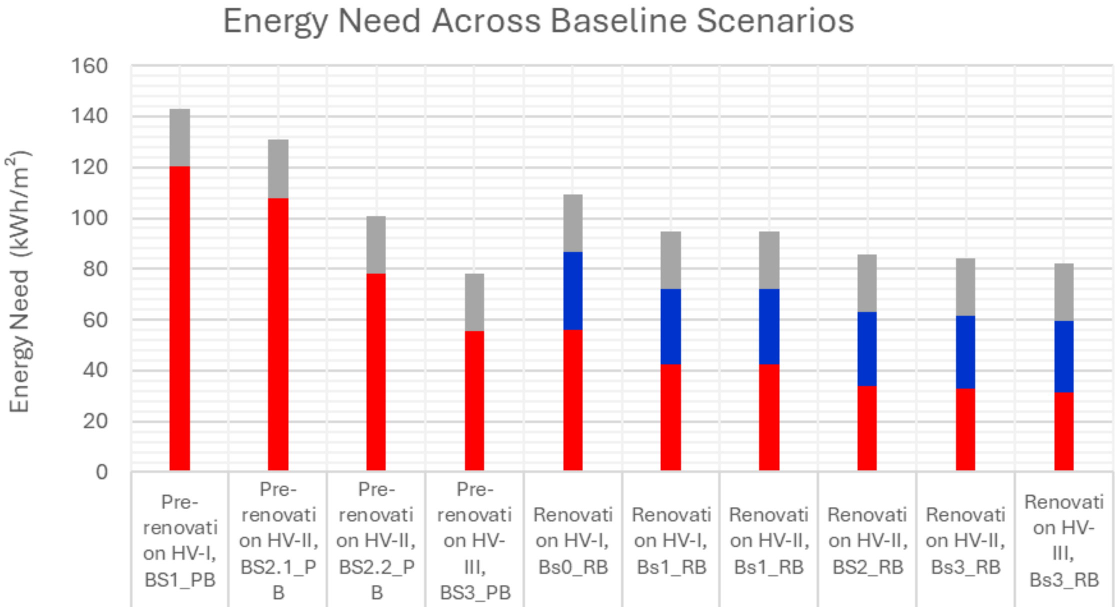
The operational information have been implemented into the model to reflect the standard use of the building typologies, as described in section 4.1.1. As far as the generation system is concerned, there is a centralized gas boiler, which produces both domestic hot water and heating. In the following tables are reported the U value for each building component, the ACH due to infiltration and the overall efficiencies of the technical systems (η_{sys}) for Extended building archetype analysed.

	Pre-renovation			Renovation					
	Pre-re, HV-I, BS1_PB	Pre-re, HV-II, BS2.1_PB	Pre-re, HV-III, BS3_PB	Re, HV-I, Bs0_RB	Re, HV-I, Bs1_RB	Re, HV-II, Bs1_RB	Re, HV-II, BS2_RB	Re, HV-II, Bs3_RB	Re, HV-III, Bs3_RB
U-Value [W/m²K]									
Exterior wall	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.28	0.28
Internal wall	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36
Ground floor	1.75	1.75	0.61	0.28	0.28	0.28	0.28	0.28	0.28
Interior floor	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94
Attic floor	2.01	2.01	2.01	0.27	0.27	0.27	0.27	0.27	0.27
Roof	1.93	1.93	0.65	1.93	1.93	1.93	1.93	1.93	0.65
Windows	5.7	2.9	2.9	5.7	1.4	1.4	1.4	1.4	1.4
Air Change Rate [h⁻¹]									
ACH	7.5	6	4.5	4.5	3	3	3	3	3
Overall efficiency of technical systems									
$\eta_{sys, heating}$	0.73	0.73	0.73	0.89	0.89	0.89	0.89	0.89	0.89
$\eta_{sys, cooling}$	-	-	-	2.23	2.23	2.23	2.23	2.23	2.23

Table 3.8 Main information on U-value, Air change Rate for infiltration and overall efficiency of the technical systems adopted in the different Pre-renovation and Renovation baseline scenarios for the Extended building archetype.

Following the estimation of the main output related to energy, comfort and IAQ aspects for each baseline scenario are presented.

Energy Need

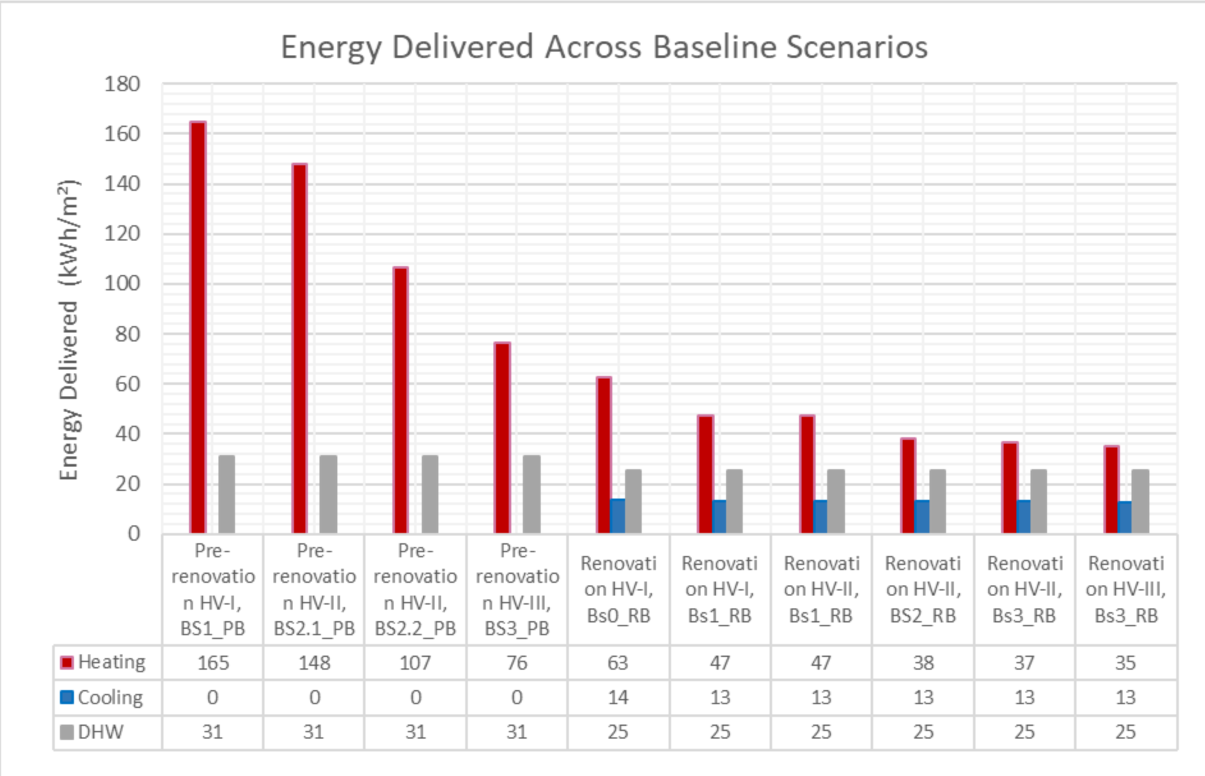


	Pre-renovation HV-I, BS1_PB	Pre-renovation HV-II, BS2.1_PB	Pre-renovation HV-II, BS2.2_PB	Pre-renovation HV-III, BS3_PB	Renovation HV-I, Bs0_RB	Renovation HV-I, Bs1_RB	Renovation HV-II, Bs1_RB	Renovation HV-II, BS2_RB	Renovation HV-II, Bs3_RB	Renovation HV-III, Bs3_RB
DHW	23	23	23	23	23	23	23	23	23	23
Cooling	0	0	0	0	30	30	30	29	29	28
Heating	120	108	78	56	56	42	42	34	33	31

Figure 3.29 Comparison of Energy Need (heating, cooling, and DHW) results for all baseline scenarios.

The graph shows how heating need is significantly reduced across renovation scenarios, while cooling demand only appears once systems are added. The best result is achieved in scenario renovation HV-II, Bs3_RB, where heating demand drops by nearly 69% compared to the specific pre-renovation baseline HV-II, Bs2.1_PB, with the lowest cooling demand as well. Domestic hot water demand remains the same in all scenarios because it is not affected by the building envelope or HVAC system upgrades. This result is mainly due to the insulation of both the horizontal and vertical envelope, the replacement of existing windows with double glazing and the reduction of air infiltration. Conversely, in the most conservative scenario HV-I, Bs1_RB, the maximum possible reduction is approximately 65% compared to the pre-retrofit baseline HV-I, Bs1_PB. This result is due to the poor thermal insulation of the building envelope, where only the floor against the ground and the ceiling towards the attic are insulated, in addition to the repair of existing windows (with a reduction in air infiltration).

Energy Delivered

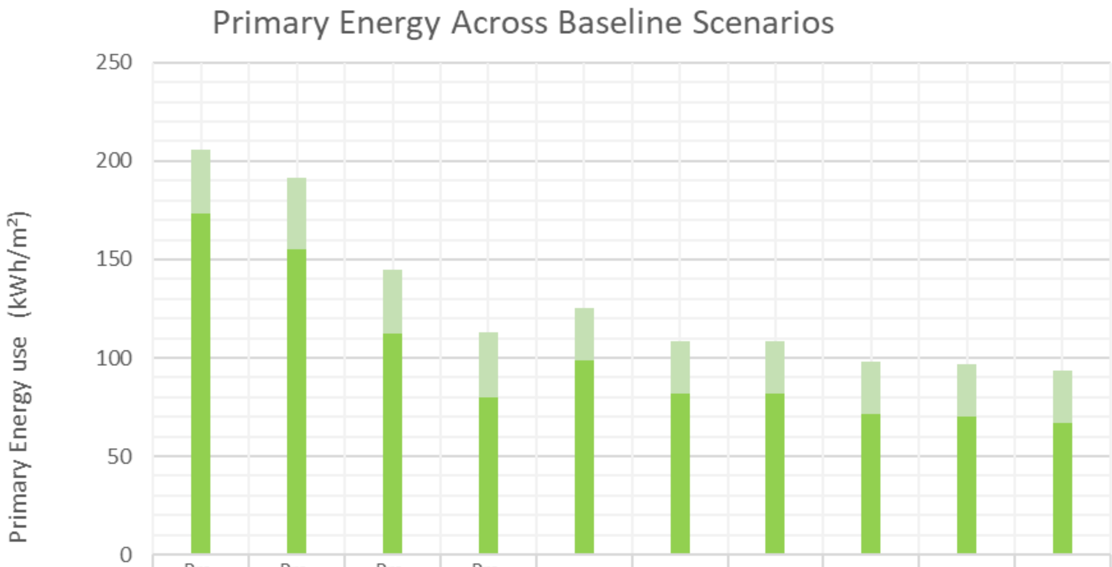


	Pre-renovation HV-I, BS1_PB	Pre-renovation HV-II, BS2.1_PB	Pre-renovation HV-II, BS2.2_PB	Pre-renovation HV-III, BS3_PB	Renovation HV-I, Bs0_RB	Renovation HV-I, Bs1_RB	Renovation HV-II, Bs1_RB	Renovation HV-II, BS2_RB	Renovation HV-II, Bs3_RB	Renovation HV-III, Bs3_RB
Heating	165	148	107	76	63	47	47	38	37	35
Cooling	0	0	0	0	14	13	13	13	13	13
DHW	31	31	31	31	25	25	25	25	25	25

Figure 3.30 Comparison of Energy Delivered (heating, cooling, and DHW) results for all baseline scenarios. It should be noted that Energy Delivered for heating and DHW refers to thermal energy, while that for cooling refers to electrical energy.

This graph highlights how heating energy delivered decreases after renovation, especially in advanced scenarios. Similarly to the results obtained for energy need, the most efficient outcome is again in renovation HV-II, Bs3_RB, which lead a reduction of about 75% compared to the pre-renovation baseline HV-II, Bs2.1_PB, which combines the lowest heating need with limited cooling requirements. Conversely, in the most conservative scenario HV-I, Bs1_RB, the maximum possible reduction is approximately 71% compared to the pre-retrofit baseline HV-I, Bs1_PB.

Primary Energy Use

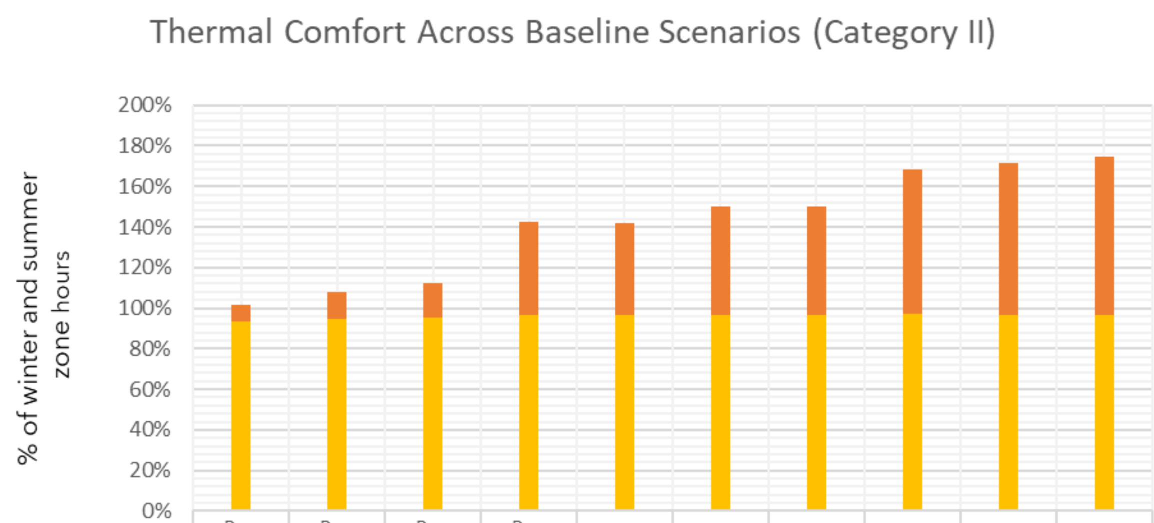


	Pre-renovation HV-I, BS1_PB	Pre-renovation HV-II, BS2.1_PB	Pre-renovation HV-II, BS2.2_PB	Pre-renovation HV-III, BS3_PB	Renovation HV-I, Bs0_RB	Renovation HV-I, Bs1_RB	Renovation HV-II, Bs1_RB	Renovation HV-II, BS2_RB	Renovation HV-II, Bs3_RB	Renovation HV-III, Bs3_RB
Domestic hot water	33	36	33	33	27	27	27	27	27	27
heating and cooling	173	155	112	80	99	82	82	72	70	67
Energy saving %					39%	47%	43%	49%	33%	17%

Figure 3.31 Comparison of Primary Energy (heating/coo The percentage indicates the reduction in primary energy compared to the related pre-renovation scenario. ling and DHW) results for all baseline scenarios.

The graph shows a clear reduction in primary energy use as renovation measures and system improvements are introduced. Pre-renovation scenarios have the highest primary energy demand, dominated by heating and cooling PEU, while domestic hot water remains constant across all cases. Once high-efficiency systems are implemented, primary energy consumption decreases significantly, reaching the lowest value in scenario renovation HV-III, Bs3, which provide a reduction with respect of the pre-renovation baseline equal to the 17%. However, the scenario that results in the greatest reduction in primary energy is HV-II, Bs2_RB, which achieves a 49% reduction compared to the pre-renovation baseline HV-II, Bs2.1_PB.

Thermal Comfort

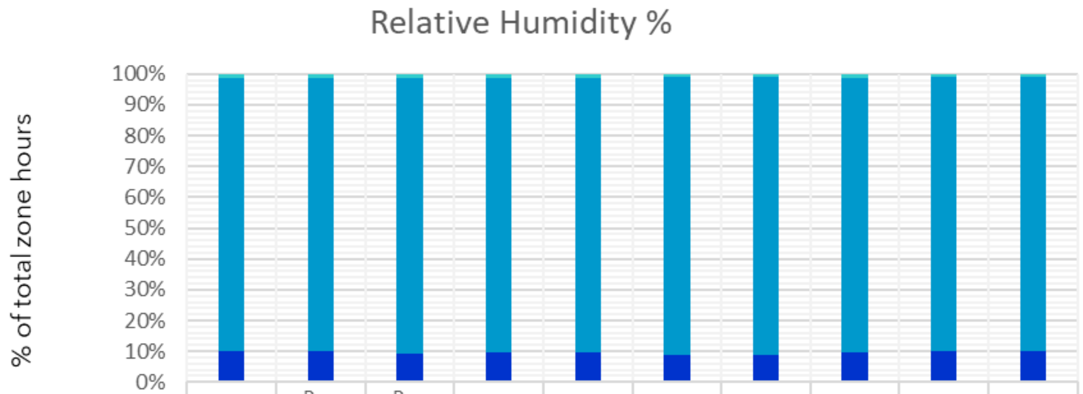


	Pre-renovation HV-I, BS1_PB	Pre-renovation HV-II, BS2.1_PB	Pre-renovation HV-II, BS2.2_PB	Pre-renovation HV-III, BS3_PB	Renovation HV-I, Bs0_RB	Renovation HV-I, Bs1_RB	Renovation HV-II, Bs1_RB	Renovation HV-II, BS2_RB	Renovation HV-II, Bs3_RB	Renovation HV-III, Bs3_RB
Winter period - h	6273	9775	12750	34238	33711	39814	39814	52666	55930	58055
Summer period - h	35122	35598	35853	36176	36312	36346	36346	36550	36261	36176
Winter period %	8%	13%	17%	46%	45%	53%	53%	71%	75%	78%
Summer period %	94%	95%	96%	96%	97%	97%	97%	97%	97%	97%

Figure 3.32 Comparison of Thermal Comfort (number of hours and % of time for winter and summer period inside CATII) results for all baseline scenarios.

The figure presents the number of hours within Category II thermal comfort limits for each baseline scenario, before and after renovation. Higher values indicate better comfort performance, as a greater share of occupied hours remains within the acceptable range defined by EN 16798-1. Before renovation, all cases perform well in summer, with 94–96% of the hours meeting comfort criteria, while winter comfort is very low at only 8–46%. After renovation, summer comfort stays high in all scenarios (97%), meaning the building maintains good comfort during warm months. Winter comfort, however, changes much more: some scenarios still remain low (around 45%), while others show major improvements, reaching 78%. The best result is in renovation HV-III, Bs3, where winter comfort reaches 78%, meaning the most winter periods meet the Category II limits.

Relative Humidity



	Pre-renovation HV-I, BS1_PB	Pre-renovation HV-II, BS2.1_PB	Pre-renovation HV-II, BS2.2_PB	Pre-renovation HV-III, BS3_PB	Renovation HV-I, Bs0_RB	Renovation HV-I, Bs1_RB	Renovation HV-II, Bs1_RB	Renovation HV-II, BS2_RB	Renovation HV-II, Bs3_RB	Renovation HV-III, Bs3_RB
Above 70%	2%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Between 30% & 70%	88%	89%	90%	89%	89%	90%	90%	89%	89%	89%
Below 30%	10%	10%	9%	10%	10%	9%	9%	10%	10%	10%
Above 70% - h	2244	2040	2074	1768	1751	1632	1632	1785	1904	1887
Between 30% & 70% - h	131631	132124	133348	132617	132685	133824	133824	132498	132260	132209
Below 30% - h	15045	14756	13498	14535	14484	13464	13464	14637	14756	14824

Figure 3.33 Comparison of Relative Humidity results for all baseline scenarios. The graph shows the number of hours and % of time inside the optimal range for RH (30-70%), below 30% of RH and above 70% of RH.

The graph shows the number of hours during which relative humidity (RH) fell below 30%, between 30–70%, and above 70%, across different periods. Most hours fall within the 30–70% range, indicating that indoor humidity is generally maintained within the recommended level, with percentages ranging from 88% to 90%. Very low humidity (<30%) is rare, about 10% of total hours. High humidity (>70%) decreased after renovations, from 2% pre-renovation to 1% post-renovation, showing improved humidity control. Overall, the building's humidity is mostly within the ideal range, and renovations and HVAC adjustments effectively reduced excessive humidity while very dry conditions remain uncommon.

CO_2 Concentration

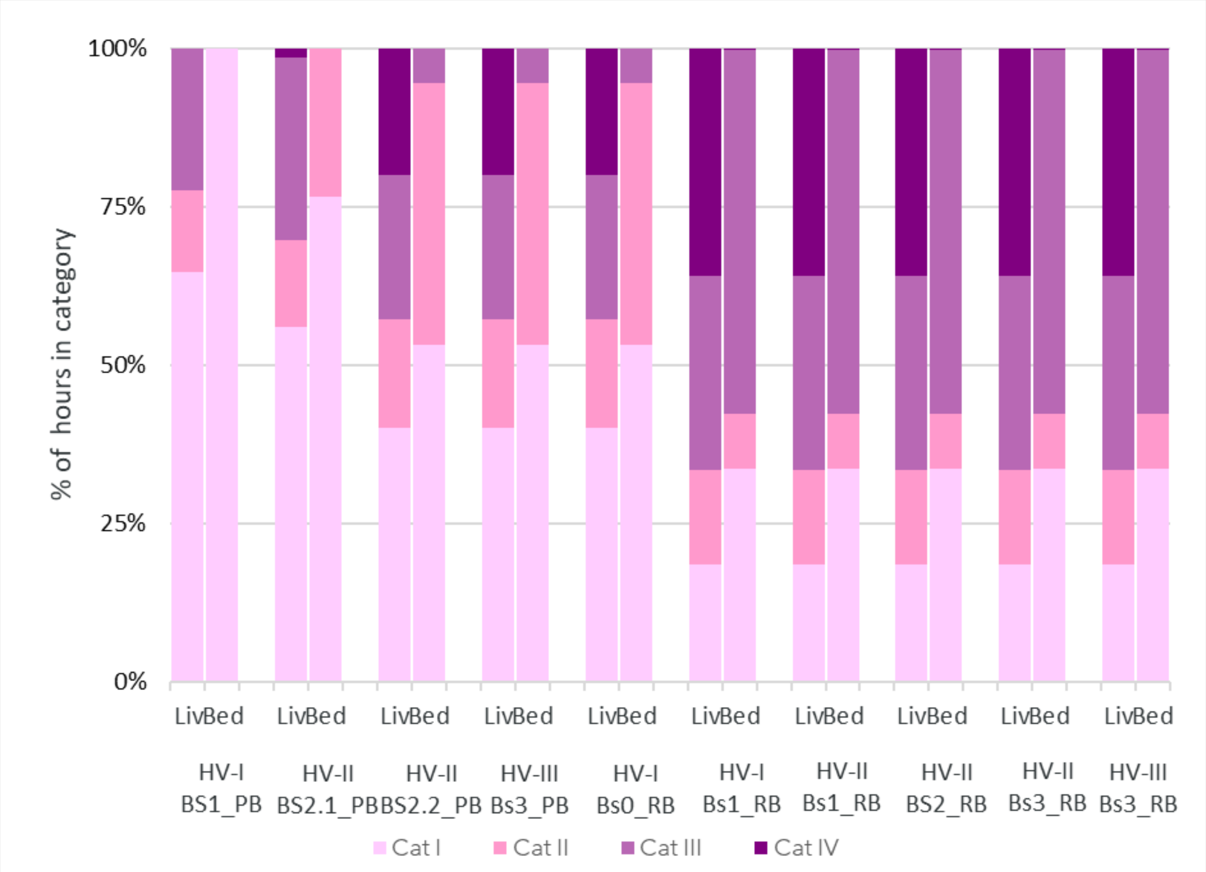


Figure 3.34 Comparison of CO2 concentration results for all baseline scenarios for the living room and the bedroom (Occ_C). The graph shows the percentage of time for each category: CAT II includes CAT I, CAT III includes CAT I and II, and CAT IV encompasses all prior categories.

According to the results in the figure above, in the first pre-renovation scenario, CO_2 concentration levels throughout the year for the living room stay within CAT I 89% of the time and within the CAT II zone for the remaining 11%. In the final post-renovation scenario, this shifts to 42% in CAT I, 23% above CAT I but within CAT II, 33% up to the limit of CAT III, and the remaining 3% in the CAT IV. For the bedroom in the initial pre-renovation scenario, the CO_2 concentration is distributed as 66% within CAT I, 32% in the zone between CAT I and CAT II, and the remaining 2% within CAT III. In the final post-renovation scenario, this shifts to 23% within CAT I, 10% in the zone between CAT I and CAT II, 38% between CAT II and CAT III, and 29% in CAT I. It should be noted that the worsening of the air quality is mainly due to the replacement of windows, which causes a reduction in air infiltration. This issue will need to be adequately addressed in more advanced renovation scenarios, which may involve the implementation of more effective natural ventilation strategies or the installation of mechanical ventilation systems.

3.1.5. Lessons learnt

In conclusion, based on the results presented above, it can be stated that all the analysed archetypes show a similar trend. Regarding energy demand and consumption, the best scenario is the one in which the building envelope is further insulated, and the windows are replaced, resulting in a reduction in heating energy consumption of approximately 68–75%. Although the cooling service is added in the post-renovation scenarios, leading to an increase in energy demand compared to the initial condition, this allows for improved summer thermal comfort. Concerning primary energy, the best results show a reduction of 41–49% compared to the pre-renovation situation. This indicates that additional strategies and more efficient solutions will be required to achieve a reduction equal to or greater than 60%.

With respect to thermal comfort, in the pre-renovation scenarios the conditions are unfavourable, especially in winter, due to the poor insulation of the building envelope. In the summer period, the situation is not as disadvantageous; however, the implementation of a cooling system is considered necessary to mitigate heat waves. In the post-retrofit scenarios, conditions improve in both winter and summer. It should be emphasized that the optimal winter condition is achieved through wall insulation, which allows more favourable operative temperatures to be reached; otherwise, similar conditions would require an increase in the heating setpoint.

Regarding relative humidity, both the pre-renovation and post-renovation scenarios show favourable conditions (with more than 88% of hours within the optimal range), with a slight improvement following the retrofit interventions.

Finally, about CO_2 concentrations, a worsening of the conditions is observed when window replacement measures are applied, due to a reduction in air infiltration. This highlights that, to improve indoor air quality conditions, it would be necessary to implement a mechanical ventilation system or to increase natural ventilation.

3.2. Belgium

For Belgium, four archetypes were selected within the HeriTACE project: the middle-class townhouse as the most prevalent one, the modest house, the private mansion and the multi-family townhouse. More details about the archetypes can be found in 'D5.1: Case-study selection at building and neighbourhood levels' (Maton et al., 2024).

For each archetype, a dynamic coupled building energy simulation and indoor air quality model is made. The archetypes are modelled and simulated in the simulation software Dymola using the Modelica Language, an open-source, object-oriented modelling language. The object-oriented character makes it easy to re-use and combine models from different Modelica libraries to model the building, its HVAC systems and occupants (Modelica, n.d.). For the modelling of the Belgian archetypes, the main libraries used are the IDEAS (Integrated District Energy Assessment Simulations) library, version 4 (Jorissen et al., 2018; De Jonge et al.,2021) combined with some proprietary Modelica classes. The IDEAS library is an open-source library which include building component models (both for thermal and airflow modelling).

For the Belgian archetypes, the archetype level verification method is used. This verification is done for the middle-class townhouse. The choice for this archetype is twofold. First, for this type of building, the most data was collected during previous tasks of the project (T3.1, T2.1 and T4.1). Second, this is the most prevalent archetype in the region. For the four archetypes, all the variations of the pre-renovation and renovation baseline are modelled, simulated and assessed. For this report, the possibility of changing the building function is not included.

3.2.1. General assumptions

Coupled BES-IAQ

The archetype models are thermal models coupled with pressure driven interzonal and infiltration airflow models. This means that not only heat is transferred trough building elements (interior elements or boundary elements), but that there are also models to represent the airflow through building elements and between rooms. With this state-of-the-art multizone airflow modelling included, it is also possible to obtain outputs related to the flow of moisture and CO_2.

Multi-zone approach

In traditional energy calculation methods, such as the energy performance certificate, the whole building is assumed to be one thermal zone, with a uniform temperature across the whole zone. For this research, a multi-zone approach is adopted to ensure an accurate representation of the (dynamic) behaviour of the building. In practice, each room of the building is treated as a separate zone. Only the cellar and the attic are considered one zone (so the possible subdivisions here are neglected).

For the multi-family townhouse, the multi-zone approach is modified to ensure that the computational time of model was within realistic boundaries. For this archetype, all the rooms of the same function that are assumed to be heated and used together are the same thermal zone. For example, the living room, dining room and kitchen are the same zone, but the bedroom is a separate zone. This results in the following amount of zones for each archetype:

Archetype	Amount of zones
Middle-class townhouse (MCT)	18
Modest house (MH)	12
Private mansion (PM)	20
Multi-family townhouse (MFT)	21

Table 3.9 Number of zones in each Belgian archetype model.

Weather data

For dynamic simulations, the transient boundary weather is an important parameter. By using a weather file with the necessary data of the location that is investigated, an accurate assessment of the energy use and IAQ is possible. A weather file in the Dymola software/Modelica Language is compiled of different parameters for each time step (mostly hourly data): temperature, relative humidity, atmospheric pressure, direct and diffuse solar irradiation, wind speed and wind direction.

For the verification of the simulation model, climate data is preferably obtained near the location where the measurement data is gathered, Ghent in this case. The closest weather station where qualitative data could be obtained from was in Melle, a municipality located 10 km from the centre of Ghent. All the necessary data is obtained from the Royal Meteorological Institute of Belgium (n.d.) for the period 1st Jan 2024 until 10th November 2025. An important notice here is that Melle is a rather rural municipality, while the measured cases were situated in a dense city centre. Consequently, the cases are subject to the urban heat island effect, which causes higher outdoor air temperatures in the city than outside. When comparing temperature data from the city centre with the data from Melle, this effect is clearly visible. Predominantly, the minimum temperatures are higher in the city centre than outside. However, there is not sufficient data from the centre of Ghent available to use this for the simulations.

A Typical Meteorological Year (TMY) weather file is used for the baseline simulations. For the Belgian archetypes, the climate data from Uccle is used. This is the typical, Belgian average file (2007-2021) used in building energy simulations.

Occupancy

For the baseline simulations as well as for the verification, a standardized occupancy is assumed for all archetypes. Full occupation of the building is assumed, meaning that every living room is used, that every bedroom is occupied and that all occupied rooms are heated.

Heating

In 'D3.2: Comfort and IAQ in heritage townhouses' (De Jonge et al., 2025), the heating profile for the baselines was already defined. A typical and realistic heating schedule is proposed for the baseline, presuming a high comfort level and all the rooms that are used being heated. The chosen setpoints are based on the design operative temperatures for category II in EN 16798-1:2019, the work of Verbruggen (2021) and the observations from the measurements.

The living room is heated to a setpoint of 20°C during the day. During the night, a setback of 5°C is applied, decreasing the setpoint to 15°C. The thermostat in the living room determines the operation of the central heating system, so when there is a setback in the living room, there is de facto also a setback in the other rooms. Use of local thermostatic radiator valves allows the user to change the setpoint temperatures in the other rooms as well. The bedrooms will be heated to 18°C during the day, the hallways and veranda to 16°C. The bathroom is heated to 24°C, but only when it is in use during a few hours in the morning and in the evening. The other hours, the valve is assumed to be manually adjusted to correspond to a setpoint temperature of 18°C.

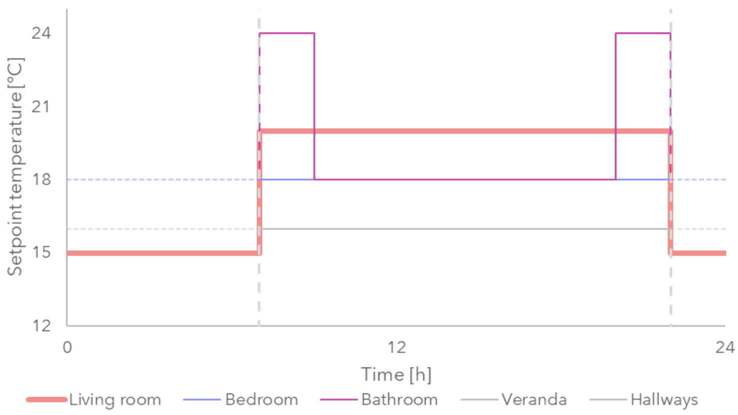


Figure 3.35 Baseline heating schedule

Occupancy profile

In line with the previous two assumptions – all rooms occupied and the heating profile – a preliminary occupancy profile is proposed, indicating at each time step if occupants are asleep, away or present. The schedule assumes that there is someone present during the day to match the heating being on during the day. Furthermore, all the occupants are assumed to be working day shifts, so they are all asleep during night.

From this preliminary input, the EROB tool (Event-based Residential Occupant Behaviour tool) is used to get detailed occupancy schedules. This tool is based on the work of Verbruggen (2021) and the adjustments of Van de Putte (n.d.). A 10 minute based output for each occupant is obtained for the living room, kitchen, office, bathroom and the different bedrooms. From this output, a weekly schedule is compiled and repeated for the whole year.

Occupancy related assumptions

The EROB tool generates several other outputs as well. For each of the following aspects, the simulation of the archetypes is done with the EROB output, which is again 10 minute based output for a weekly schedule, that is repeated for the whole year.

- An analysis of the outdoor weather data file resulted in an estimate of the clothing level (CLO) of the occupancy during day hours. The analysis follows the methodology from the EPICOOL project (Daidalos Peutz, 2009). Based on the daily outdoor running mean temperature (RMT , EN15251:2007), the CLO value is decided. If the RMT is above 15°C the CLO value is 0.5, if the RMT is below 10°C the CLO value is 0.8. Values in-between are linearly interpolated. While asleep, a pessimistic (safe) value of 0.8 is assumed regardless of the seasonal variation;

- The CLO value together with the normalised metabolic rate value (MET) which is MET=1.2 awake and MET=0.7 asleep (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2013) are inputs to a metabolic heat gain model based on the Fanger heat balance model. The sensible heat gains of occupants are not considered to be constant but rather a function of indoor environmental parameters (air temperature, mean radiative temperature) and the CLO and MET value of the occupants;

- The considered CO_2 emission rate of occupants is 20l/h during the day and 13.6 l/h while asleep. This is in line with the assumptions made for the IEQ classes limits of the EN 16798 standard (Table B.12) which will be used to evaluate the IEQ performance of the building simulation model simulation results;

- For moisture production from respiration the CEN/TR 14788:2006 (Annex A) is followed: 55g/h when awake, 40g/h when asleep;

- Window opening behaviour: a schedule for the opening (1) or the closing (0) of the window is used for each room. In winter one of the two operable parts is opened for a width of 5 cm and in summer one of the two operable parts of the window is opened completely (width of 30cm);

- Domestic hot water (DHW): a tapping profile for DHW is generated based on the amount of habitants. It is used to assess the energy need for the production of DHW. Only showers, bathroom tap and kitchen tap are assessed. A hot water use at the tapping point (at 40°C) between 23.5 l per day per person (for five inhabitants) and 38 l per day per person (for one inhabitant) is assumed based on the EROB output;

- Appliances & lighting: for each room, the heat gains from appliances and lighting is obtained, both for convective as for radiative heat gains. The assessed appliances are a freezer, a refrigerator, a HiFi installation, an iron, a vacuum cleaner, PC's, a printer, TV's, an oven, a microwave, a hob, a kettle, a dishwasher, a washing machine, a tumble dryer and smartphones;

- Moisture production of activities: the moisture production is obtained for showering, cooking and doing the dishes. Some conditions are put in place to make these assumptions more realistic. Regarding the showering: an occupant only showers when no other occupant is present and the occupant can only take a shower once every 12 hour. The moisture generation from a shower is 0.5 l/s during 10 minutes. Regarding the dish washing, a generation profile of 0.5 l/s is assumed. Regarding the cooking, a generation profile is assumed of 0.6 l/s for breakfast, 1 l/s for lunch and 1.5 l/s for dinner. All values are based on CEN/TR 14788:2006.

Building context and obstructions

Each archetype is a terraced townhouse and is assumed to be located in a historic city centre. This has consequences for the assumed boundary condition.

Firstly, the neighbouring building is assumed to be a similar building, but mirrored. Each heated space borders another heated space at the neighbours, as can be seen on figure Figure 3.36. Consequently, the party walls are assumed to be adiabatic.

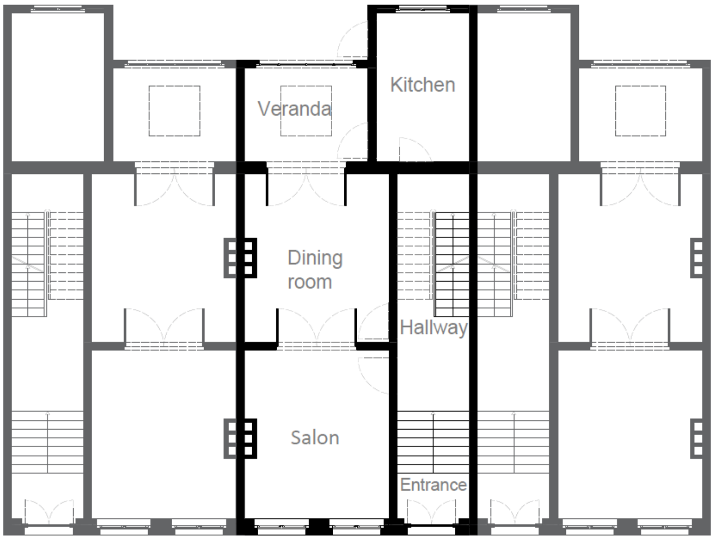


Figure 3.36 Illustration of spatial organization of neighbours

Secondly, the building is shaded by its opposite neighbours. Again, a similar building is assumed in front of the archetype building. A separation of 10m is assumed, a consequent of the relatively narrow streets in the city centre. Additionally, a similar building is also assumed in the back with a separation of 30 m (and mirrored), assuming a larger garden area within the building block. Also the annexes of the neighbouring and the own building can cast shadow on certain construction elements, which is also accounted for.

Figure 3.37 Illustration of position of neighbouring buildings

Thirdly, the windows are always recessed in the wall. This also casts a shade on the windows. A depth of 20 cm is assumed for the main building, 10 cm for the annexes.

Lastly, the location within an urban centre causes the wind pressure to be different than the wind pressure in open field. A wind speed modifier is applied, calculated according to ASHRAE handbook: fundamentals (2005). A wind boundary layer thickness δ of 460 m and a velocity profile exponent a of 0.33 are assumed.

Radiator power

The determination of the radiator power in the different archetypes is of high importance. It will determine if in renovation scenarios lower supply temperatures will still be adequate to compensate for the heat losses. An underestimation of the actual installed pre-renovation baseline heating power will make lowering the supply temperature (and thus switching to low temperature heat pumps based systems) very challenging in scenarios where radiators are re-used in the HVAC concept. Contrary, an overestimation will be an overoptimistic starting point.

A first approach is to determine the radiator power for the pre-renovation baseline based on the heat losses of the archetype in this baseline scenario. All the radiator powers are assumed to be determined at 90°C/70°C/20°C conditions. When comparing these results with the power of the original cast-iron radiators present in the case study buildings (although limited), it is clear that this approach would cause a structural underestimation of the heating power, as illustrated in Figure 3.38.

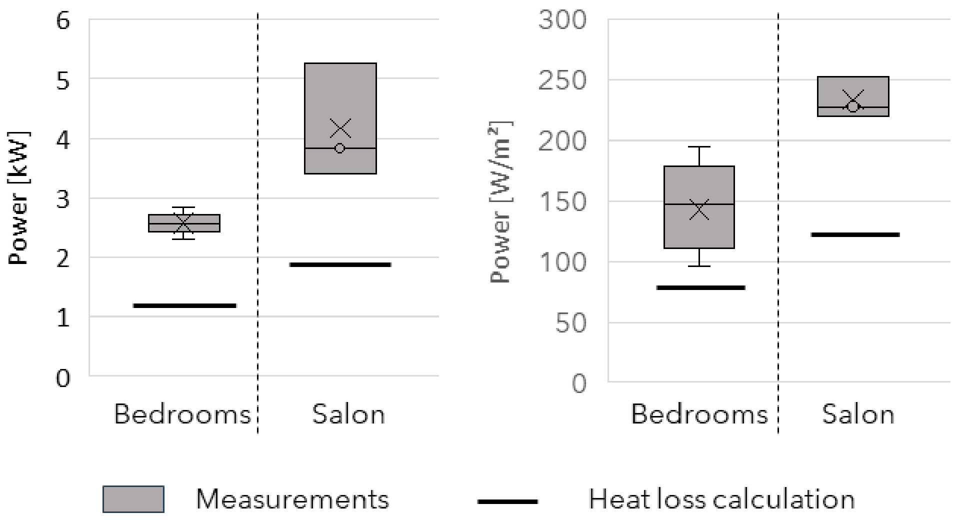


Figure 3.38 Comparison of the observed radiator powers with the calculated heat losses for the archetype.

A second approach is to use the radiator powers from the observations in the case study buildings as a guideline to determine the power needed for each function. Again, only the original cast-iron radiators are assessed at 90°C/70°C/20°C conditions. Using the absolute powers was not accurate, as the case study buildings varied greatly in size. Additionally, as it is been done with simple rule of thumb, the power of radiators is estimated based on the size of the room. In this case, using the volume of the room, rather than the surface, makes more sense: a room higher up in the building (with a lower ceiling height) showed to have lower radiator powers than the same room with a higher ceiling height lower in the building. Following this method, the values in Table 3.10 are assumed for the radiator power in the different rooms of the archetypes. For the hallway, this method rule did not seem to result in adequate results so a simple extrapolation of observed radiator powers was done.

Room	Power [W/m³]
Salon	65
Dining	50
Veranda	100
Annex	70
Bedroom	55
Bathroom	140

Table 3.10 Assumed values for the power of radiators.

Simulation setup

All the baseline simulations are carried out for one year with an output interval of 1 hour. The used solver is Cvode with a tolerance of 10^{-4}. Dymola will generate an intermediate calculation point at each event it identifies or if dynamics are identified to be faster than the hourly output interval.

3.2.2. Verification

Since the baseline description of the archetypes is not a one-to-one representation of one of the case-studies, an archetype-level verification is done. For this, the Middle-class townhouse (MCT) building is selected since this the most prevalent archetype and most measured data is available for this archetype. Since the other Belgian archetypes differ from the MCT mostly in lay-out but not significantly in construction method, the verification of the MCT also serves as a the baseline archetype verification for the larger (PM,MFT) and smaller (MH) models.

The most appropriate baseline model is selected for the verification. Table 3.11 lists the selected baseline models, as a combination of the following baseline scenarios:

Baseline scenario		Description
Envelope	MCT_BS2_PB	Pre-renovation condition, with only the windows in the back facade replaced with old double-glazed windows.
Heating	CS1_PB	Radiator based heating system with central thermostat in the living room.
Energy	ES1_RB	Central condensing gas boiler with a supply temperature of 75°C (without heating curve)

Table 3.11 Overview of selected scenarios for the verification of MCT

Furthermore, the boundary conditions of the model are changed to reflect the year 2024-2025 and location of the measured cases in Ghent. The climate data of Melle is used. Corresponding, the period where heating is on, is adapted based on an analysis of the running mean outdoor temperature. Likewise for the assumed clothing of people during day-hours. Finally, the street-side façade is oriented East, as this was the most prevailing orientation for the measured cases.

Several aspects of the simulated output with respect to indoor temperatures, CO_2 levels and energy use were compared to the information in the gathered data. Where necessary, alterations where made to the baseline models to improve the verification. These alterations are reflected in the description of the models above already.

In line with figure 2-1 in D3.2 of this project. The volume weighted overall building temperature of the building is calculated using this formula:

$$\theta_{vw}(t)=\frac{\sum_i V_i \cdot \theta_i(t)+\sum_i V_j \cdot \theta_j(t)}{V_{tot}} \quad (1)$$

With

$\theta_{vw}(t)$ [°C] The volume weighted air temperature

V_i [m³] The interior volume of the space where a measurement took place.

V_j [m³] The interior volume of the spaces where no measurement took place.

V_{tot} [m³] The total interior volume of all spaces

θ_i(t) [°C] The measured indoor air temperatures

$\theta_j(t)$ [°C] Assumed indoor air temperature of the other spaces.

The indoor temperature has a substantial impact on the building heat losses and thus the energy use. In the Belgian national EPC/EPBD calculation frameworks, the whole building volume is assumed to be isothermal with a temperature of 18°C in winter and 23°C in summer. Figure 3.39 shows the distribution of the measured volume weighted average indoor temperature during winter (Dec-Jan-Feb) and summer (Jun-Jul-Aug) for the available data. The volume weighted temperature is calculated, excluding unused attics and basements, using equation 1 for the measured cases Occ_A to Occ_C and the simulation results. For more information about the measurements results of these cases, see 'D3.2 Comfort and IAQ in Heritage Townhouses'.

Figure 3.39 shows that the assumptions in the verification model are closer to the 18°C indoor winter temperature assumed in the EPC/EPBD calculations than the measured cases. This corresponds well to the results found in the measurements that apply other heating schedules and set-point temperatures and house less occupants. The summer data indicates a larger distribution in indoor temperature levels with average and mean indoor summer temperatures around 21°C. Again, this corresponds well to the baseline description and modelling assumptions.

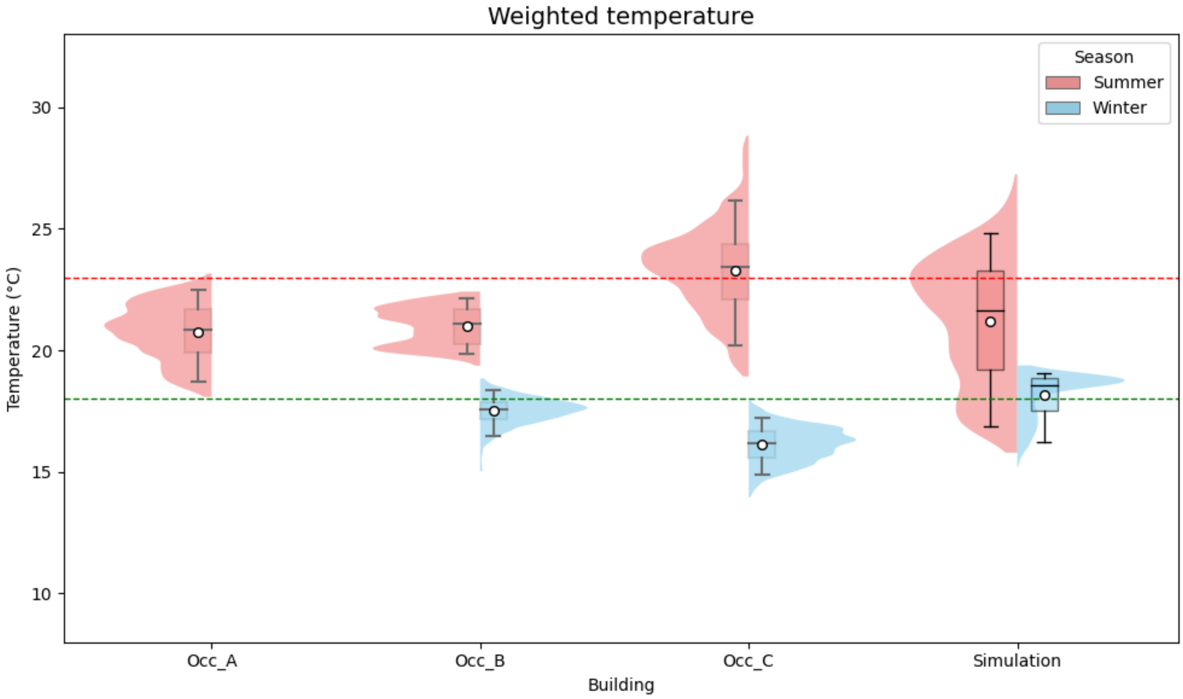


Figure 3.39 Volume weighted temperature distribution for the measured cases and the verification model.

To support this statement, Figure 3.40 and Figure 3.41 show temperature distribution graphs for the living room and main bedroom. In both cases, the results show better visual overlap. Bedroom winter temperatures are higher in the simulated case corresponding to the higher heating set-point temperature in the baseline description.

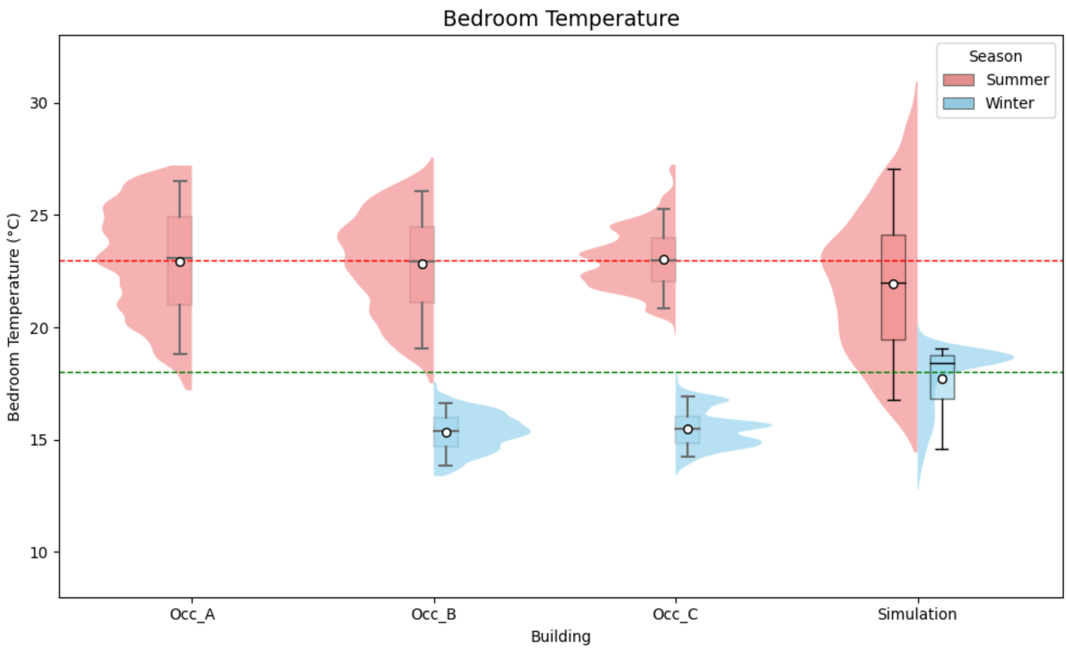


Figure 3.40 Indoor temperature distribution for the main bedroom in measured cases and verification model.

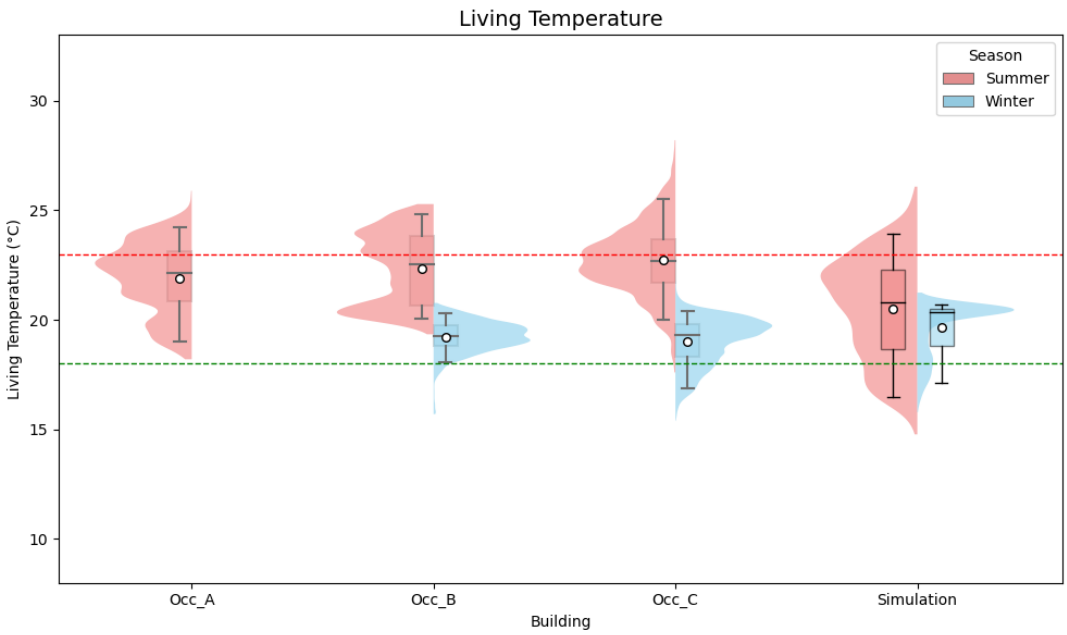


Figure 3.41 Indoor temperature distribution for the living room in measured cases and verification model.

Also CO_2 levels where verified as a means to verify the multi-zone pressure driven airflow model. Results are as expected. Figure 3.42 and Figure 3.43 show the results for living room and main bedroom.

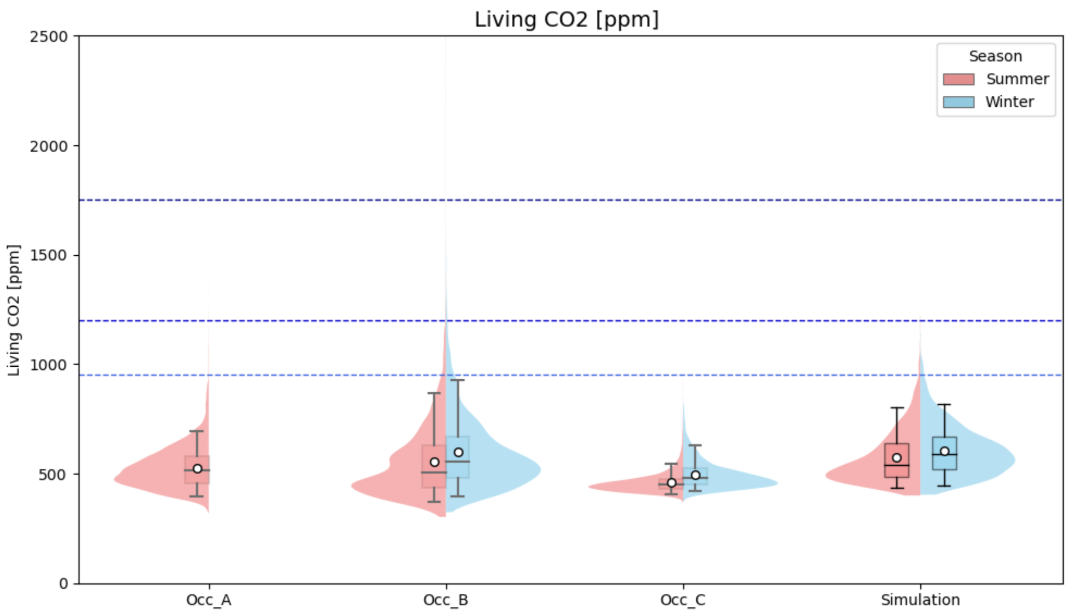


Figure 3.42 distribution of CO_2 concentrations for the living room in measured cases and verification model.

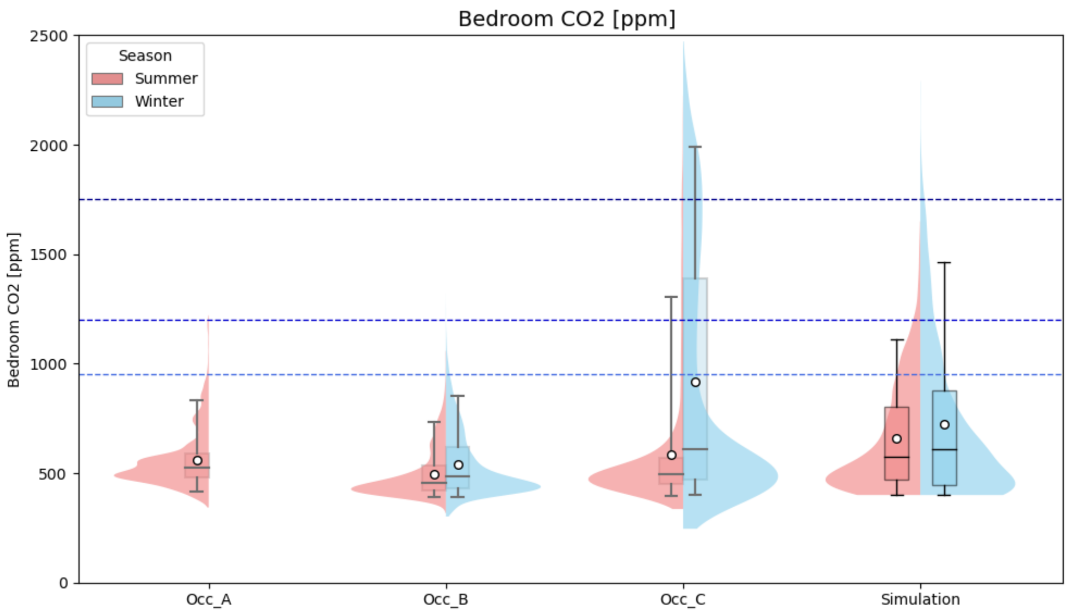


Figure 3.43 distribution of CO_2 concentrations for the main bedroom in measured cases and verification model.

Lastly, the energy need of the simulated case was verified by comparing with the energy need reported by the occupants. The simulated energy need is 26830 kWh or 156 kWh/m². Figure 3.44 shows a bar chart of the results. Most of the cases' total energy need also includes the energy needed for production of domestic hot water, because it is partially or completely provided by gas boilers (whether or not the same as for space heating). To make a fair comparison, the total energy need of the verification model also includes and estimation for the energy need for DHW production, which results in 1490 kWh for five habitants (assuming electric DHW production).

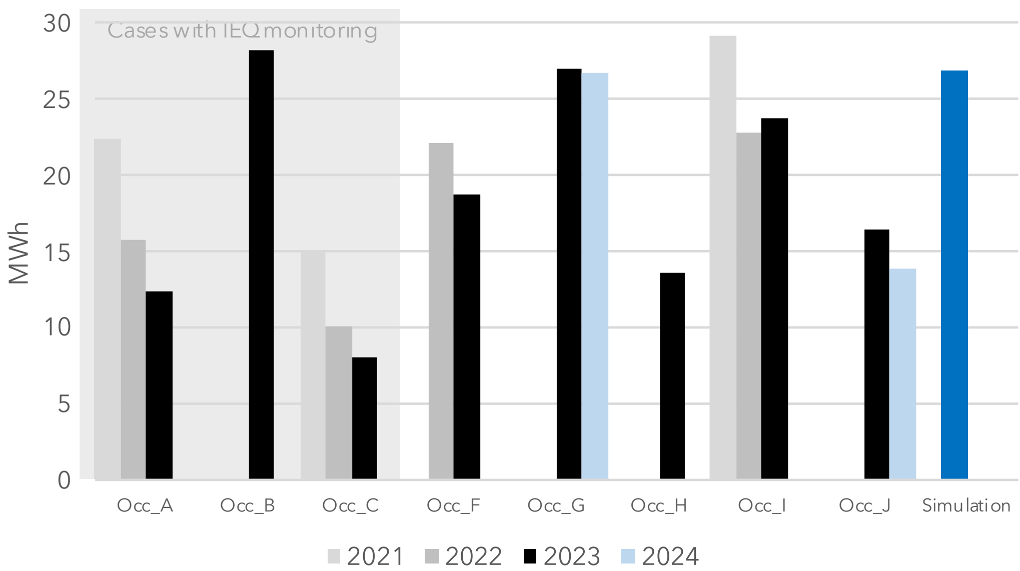


Figure 3.44 Energy need of all cases (Occ_A to Occ_J) of the MCT archetype and the verification model.

In absolute values, the energy need of the simulated verification model is of the same order of magnitude as the energy need reported in the cases. However, it is clear that there is a difference between the verification model and the assessed cases. These differences can be explained by a deviant heating pattern in the cases and the baseline heating pattern. For example in Occ_B, the heating setpoint is much lower than the 20°C assumed in the verification model. In Occ_B, the attic is heated to a very high setpoint. Another influencing parameter is the degree of renovation, Occ_I or Occ_J are cases where the building has already undergone a thorough retrofit.

Two other important differences between the cases and the verification model influence the energy need: the size of the building and the degree of use of the building. As can be seen in Figure 3.45, the energy need per unit of heated area (liveable spaces/heating system present) causes the difference between the verification model and the cases to be more pronounced. Most of the cases have a lot of surface floor area that is not heated, either because it is not necessary according to the inhabitants (in the case of a bedroom for example) or because the dwelling is oversized for the habitants and those rooms are not used. When assessing the energy need per habitant, the verification model's energy need is rather close to the reported energy need per habitant. Occ_G and Occ_H are cases where only one person lives in the whole building, resulting in a very high energy need per person.

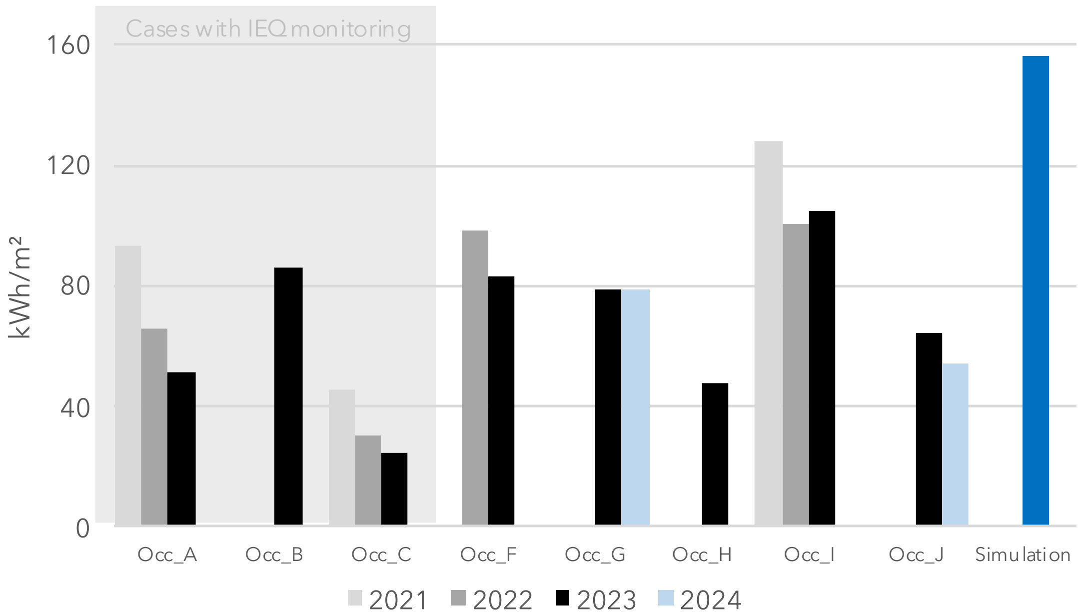


Figure 3.45 Energy need per m² of all cases (Occ_A to Occ_J) of the MCT archetype and the verification model.

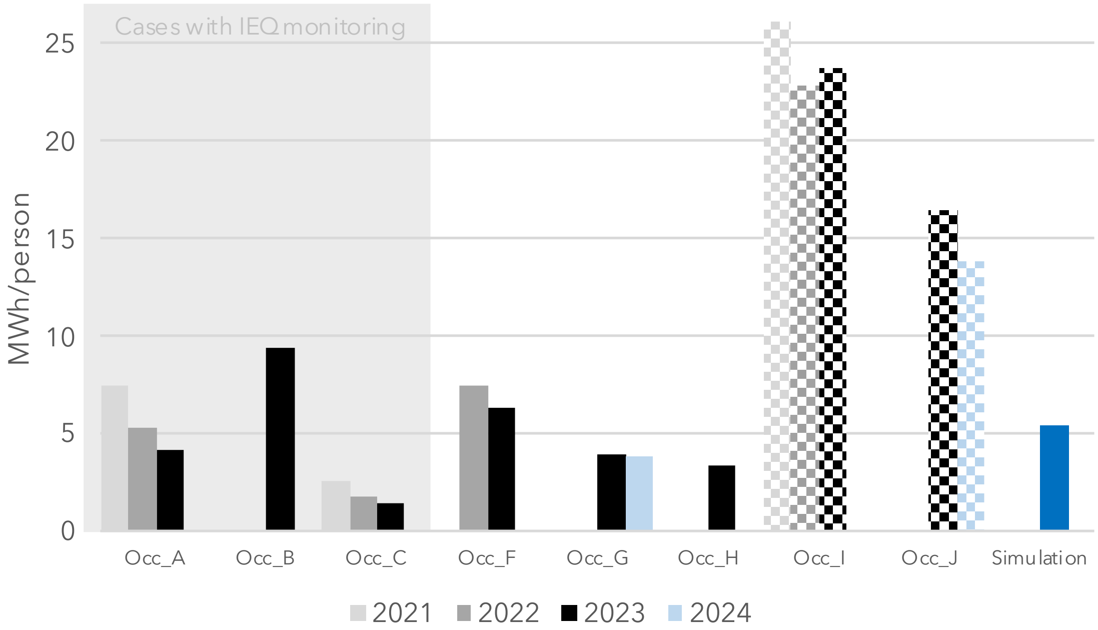


Figure 3.46 Energy need per inhabitant of all cases (Occ_A to Occ_J) of the MCT archetype and the verification model. The hatched bars correspond with cases with only one inhabitant.

In general and given the observation in the different cases, the verification model proves to be a reliable representation of the middle-class townhouse archetype. It is clear that the dynamics that are present in such a building, are correctly modelled and influence the indoor temperature, the airflow and the energy need in a realistic way. Logically, differences between the cases and the verification model occur. The archetype approach fixes the geometry and the baseline assumptions regarding occupancy, heating habits and thermal properties causes the actual results to be not directly in line with the measurements. However, the modelling approach is clearly an appropriate one that results in realistic outcomes. This approach is used to model all the archetype models, with the different baseline variations.

3.2.3. Middle-class townhouse

The 19th-century middle-class townhouse is built on narrow but deep plots, typically about six meters wide. Its facade is highly individualized, richly ornamented, and served as a public display of bourgeois status. Originally, rooms were arranged in an enfilade with a strict hierarchy: representative spaces at the front and more private ones higher up. The bel étage was the most prestigious level, featuring lofty ceilings up to five meters high. Massive masonry walls form the bearing structure of this archetype, with wooden floors as intermediate floors.

For the baseline assessment, the original organisation is not changed much. The living rooms are still located on the ground floor and all the bedrooms and bathrooms are located on the upper floors. An office is located in the annex on the first floor. The basement and attic are not in use and consequently also not heated. A family of five people is assumed to inhabit this archetype, with the main bedroom being the bedroom on the first floor at the street side. The bathroom on the first floor is assumed to be used for the people who have bedrooms on that level. The same goes for the bathroom on the second floor. Figure 3.47 gives an overview.

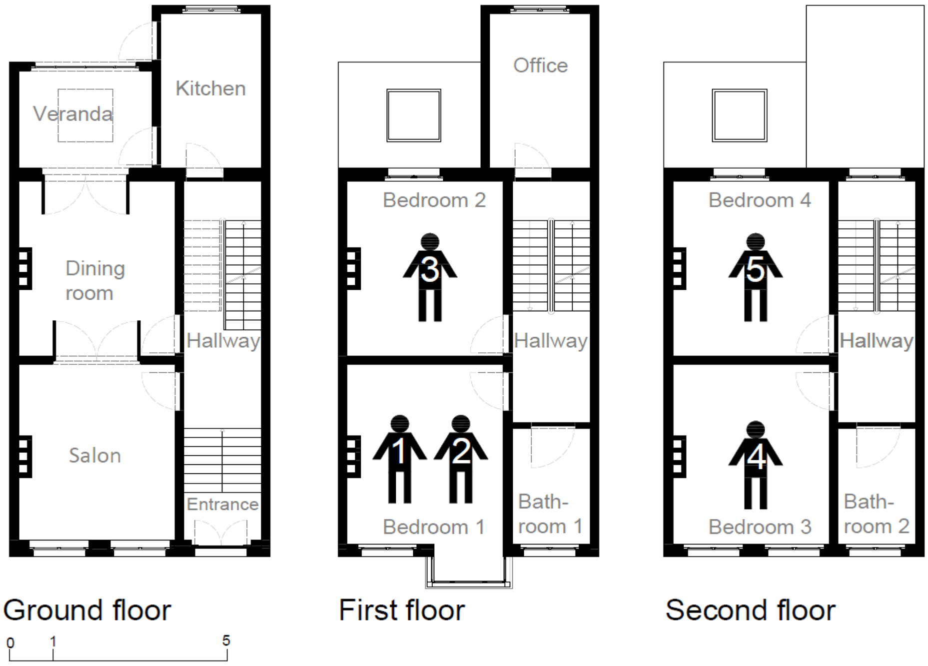


Figure 3.47 Overview of the baseline spatial organization of the MCT.

The archetype has a net heated surface of 160 m² and a net heated volume of 580 m³.

Results for pre-renovation and renovation baseline

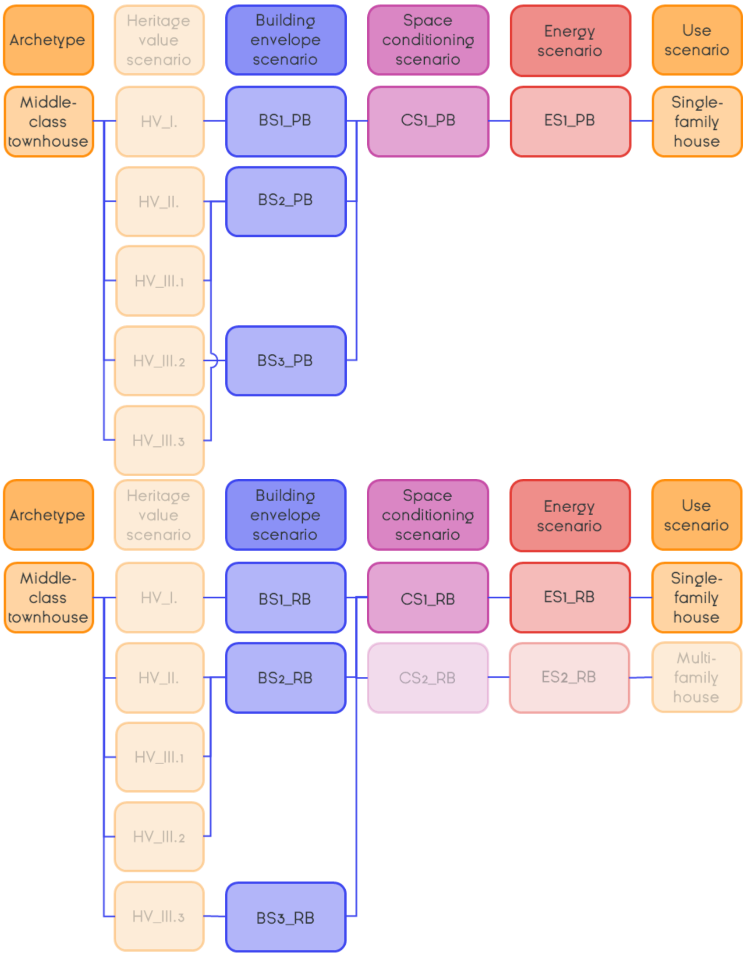


Figure 3.48 Overview of the pre-renovation (top) and renovation (bottom) baseline scenarios for the MCT.

As described in 'D5.4 baseline scenarios' (Flyen et al., 2025), the middle-class townhouse is modelled and simulated as different variations, as shown in Figure 3.48. For the simulations, the heritage value scenario is not influencing any of the results and is thus not of any importance. For this deliverable, the function of the renovation baseline is assumed to be the same as the pre-renovation baseline, a single-family house. The multi-family variant of the middle-class townhouse is not assessed.

Three different envelope scenarios are modelled for both the pre-renovation and the renovation baseline. The U-value of the different building envelope scenarios is provided in Table 3.12. Radiators with a thermostatic valve are assumed, with a central thermostat for the heating system. Regarding the pre-renovation baseline, an old condensing gas boiler with a supply temperature of 90°C and a power of 35 kW is providing the space heating, electric boilers are providing the DHW supply. For the renovation baseline, a new condensing gas boiler with a power of 35 kW is providing for the space heating. A heating curve is applied, with a supply temperature of 75°C at an outdoor 6-hour moving average temperature of -8°C and a supply temperature of 20°C at an 6-hour moving average outdoor temperature of 20°C.

Middle-class townhouse (MCT)	Pre-renovation baseline (PB)			Renovation baseline (RB)		
U-value [W/m²K]						
Component	BS1_PB	BS2_PB	BS3_PB	BS1_RB	BS2_RB	BS3_RB
Exterior front facade	1.52	1.52	1.52	1.52	1.52	0.37
Exterior back facade	1.52	1.52	1.52	0.24	0.24	0.24
Interior bearing wall	1.69	1.69	1.69	1.69	1.69	1.69
Ground floor*	3.44	3.44	3.44	3.44	3.44	3.44
Interior floor	1.36	1.36	1.36	1.36	1.36	1.36
Flat roof	0.54	0.54	0.54	0.19	0.19	0.19
Pitched roof	0.72	0.72	0.72	0.22	0.22	0.22
*Only the construction elements and the heat transfer coefficient of the interior surface are taken into account.						
U-value glass [W/m²K]						
Front windows	5.8	5.8	2.8	1.9	1	1
Back windows	5.8	2.8	2.8	1	1	1
Airtightness						
v50 [m³/hm²]	16	14	12	8	6	6
Overall efficiency of technical systems						
η_{gen}	0.89	0.89	0.89	1.08	1.08	1.08
$\eta_{distr} * \eta_{distr}$	1	1	1	1	1	1

Table 3.12 Main information on U-values, airtightness and overall efficiency of the technical systems adopted in the different PB and RB baseline scenarios for the MCT.

For the renovation baseline, a mechanical ventilation system with heat recovery is added with a constant heat recovery efficiency of 90%. The ventilation airflows are designed according to the Belgian national standard NBN D 50-001. Supply of fresh air is provided in the 'dry' rooms, extraction of air in the 'wet' rooms. An overview of the modelled ventilation flows are provided in Table 3.13. Slits beneath the doors of 2cm are assumed to provide adequate flow of air between rooms.

Ventilation flows [m³/h]		
Room	**Supply**	**Exhaust**
Salon & Dining	108	
Veranda	25	
Toilet (hallway)		35
Kitchen		150
Bedroom 1	60	
Bedroom 2	54	
Bathroom 1		100
Office	30	
Bedroom 3	54	
Bedroom 4	54	
Bathroom 2		100
Total	385	385

Table 3.13 Overview of the ventilation airflow design for the MCT

In the following paragraphs, the main output related to energy, comfort and IAQ aspects for each baseline scenario is presented.

Energy need

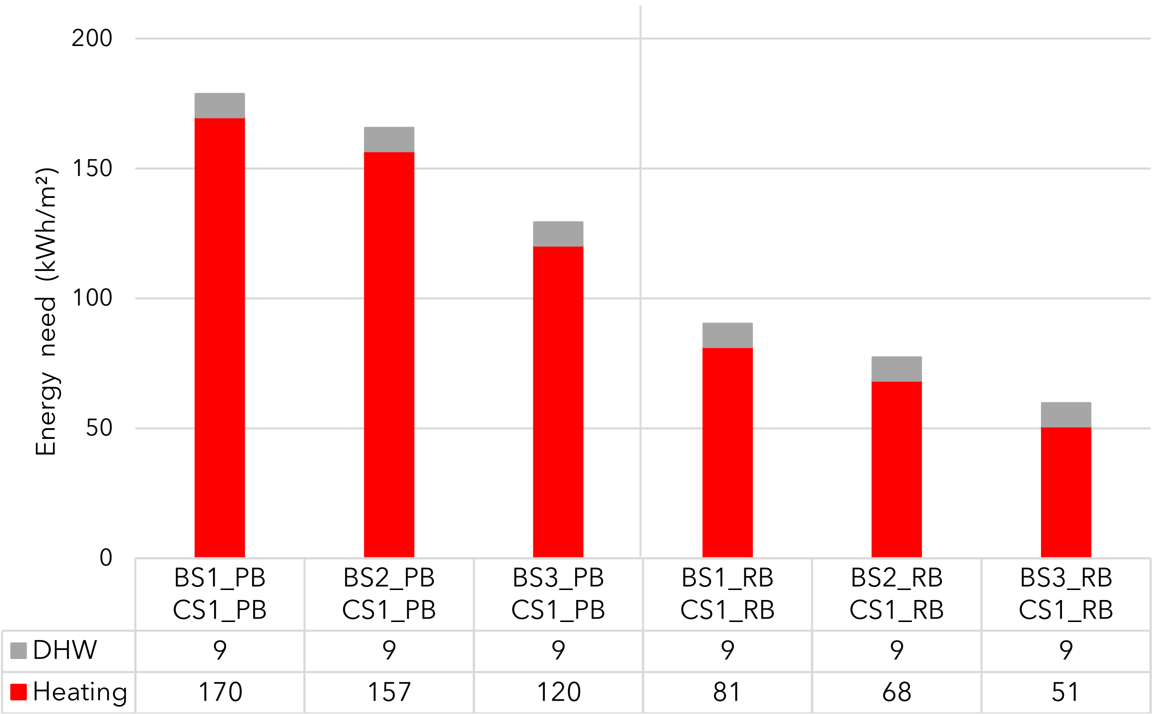
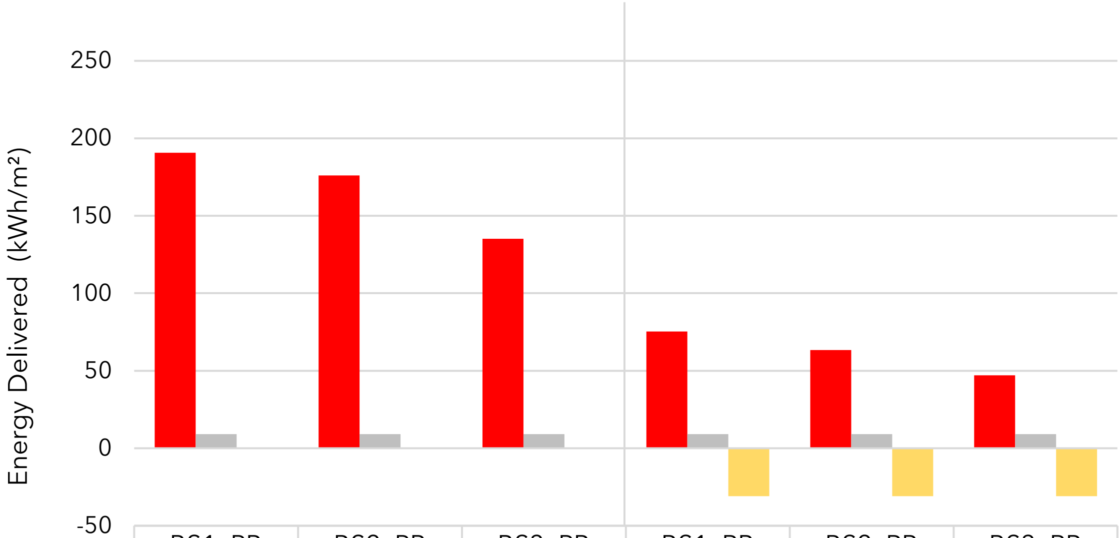


Figure 3.49 Energy need across baseline scenarios for MCT.

Figure 3.49 above clearly shows a reduction in energy need between pre-renovation and renovation baseline. Also within the pre-renovation baselines, a clear difference in energy need is notable, while only the assumptions regarding the glazing are changed. The lowest energy need is observed in the case of BS3_RB CS1_RB, where the front façade walls are insulated from the interior side in addition to the replacement of the windows. The share of energy need for DHW production is relatively small compared to the energy need for space heating.

Delivered energy

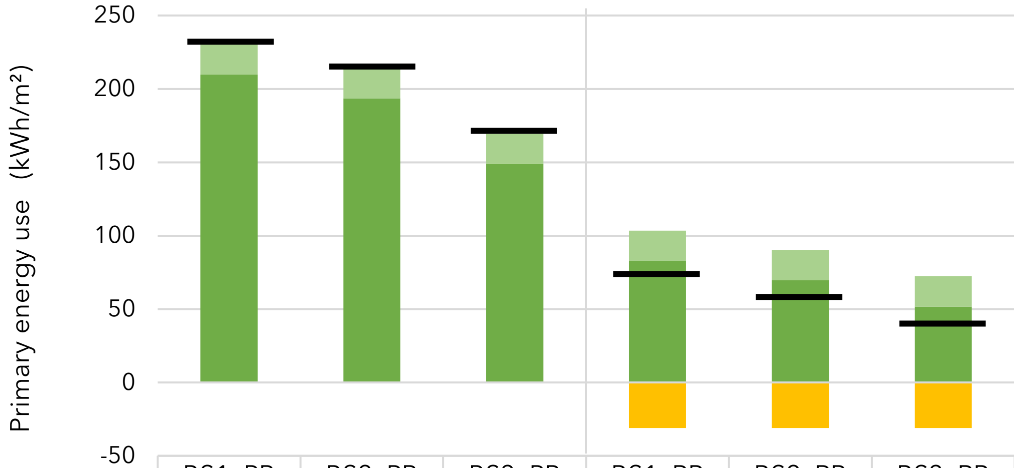


	BS1_PB CS1_PB	BS2_PB CS1_PB	BS3_PB CS1_PB	BS1_RB CS1_RB	BS2_RB CS1_RB	BS3_RB CS1_RB
Reeks1	191	176	135	75	63	47
Reeks2	9	9	9	9	9	9
Reeks3	0	0	0	-31	-31	-31

Figure 3.50 Delivered energy across baseline scenarios for MCT.

As can be observed in Figure 3.50, the distinction between pre-renovation and renovation baseline is even more pronounced when assessing the delivered energy, certainly when taking into account the energy generated by PV panels. The new condensing gas boilers with a high efficiency causes the delivered energy to be even lower.

Primary energy use



	BS1_PB CS1_PB	BS2_PB CS1_PB	BS3_PB CS1_PB	BS1_RB CS1_RB	BS2_RB CS1_RB	BS3_RB CS1_RB
Solar energy	0	0	0	-31	-31	-31
DHW	21	21	21	21	21	21
Heating	210	194	149	83	70	52
Net primary energy use		Net energy saving %		69%	74%	82%

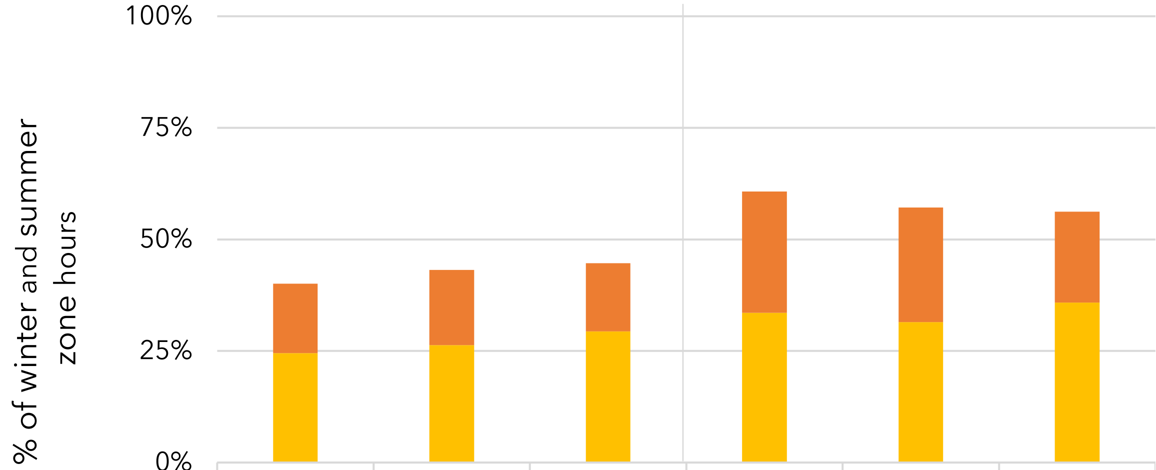
Figure 3.51 Primary energy use across baseline scenarios for MCT.

Primary energy use decreases when a whole building renovation is undergone by a heritage building. The best scenario, BS3_RB CS1_RB, has an primary energy use (excluding the benefit of solar energy) of 73 kWh/m². The energy generation from PV panels is 31 kWh/m², which causes the net primary energy use of the BS3_RB CS1_RB scenario to be 41 kWh/m², which is 82% lower than the worst pre-renovation scenario BS1_PB CS1_PB. Noteworthy is that the share of energy use of the production of DHW is larger when assessing the primary energy use because this is an electric based system. Electricity is still an energy flow with a primary energy factor (2.3) that is higher than that of natural gas (1.1).

Thermal comfort

The thermal comfort is assessed for the whole building. The concept of "zone hour" is introduced. The thermal comfort of each room is assessed separately per hour, this means that for every hour and every room, a thermal comfort category is assigned. Next, all the hours within a certain adaptive thermal comfort category are summed over the different rooms to get to a final amount of 'zone hours' within a certain category. This way, the influence of each room is integrated into the final evaluation instead of averaging out the influence of different rooms. The total amount of zone hours is the amount of hours of the assessed period multiplied by the amount of zones that are assessed.

For thermal comfort evaluation, the assessment is done for the winter period (Dec – Jan – Feb) and the summer period (Jun – Jul – Aug) separately. The attic and the basement are not taken into account, as they are not climatised. The total amount of zone hours for winter is 34560 and for summer 35328, totalling 69888 zone hours.



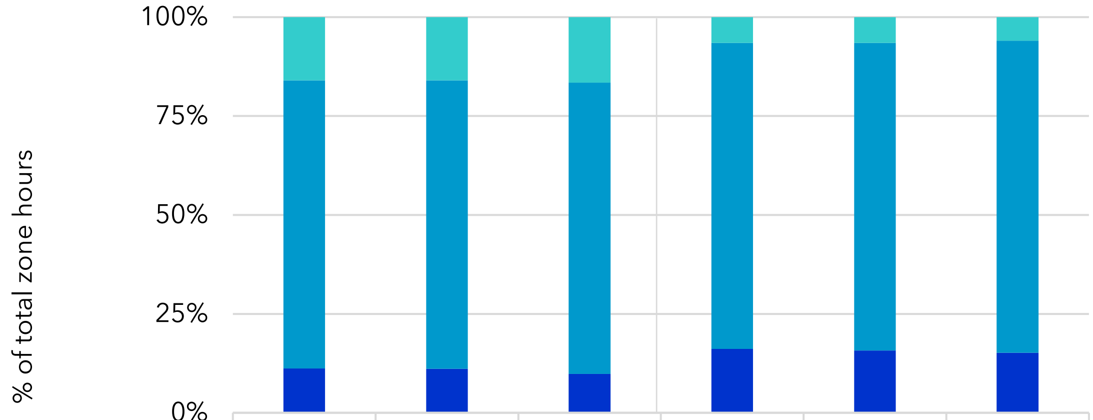
	BS1_PB CS1_PB	BS2_PB CS1_PB	BS3_PB CS1_PB	BS1_RB CS1_RB	BS2_RB CS1_RB	BS3_RB CS1_RB
Winter period - h	10850	11734	10635	19017	17945	14230
Summer period - h	17154	18408	20560	23443	21984	25043
Winter period %	16%	17%	15%	27%	26%	20%
Summer period %	25%	26%	29%	34%	31%	36%

Figure 3.52 Thermal comfort across baseline scenarios for MCT. All zone hours within comfort category I and II are depicted.

As the thermal comfort is analysed for every hour of the day, also the period during the night when the temperature is lowered (night setback) is included. This temperature can be as low as 15°C, which is outside of comfort categories I or II. Consequently, the share of the zone hours of the winter period that is within these comfortable limits is relatively limited, between 31% and 34% for the pre-renovation baselines and between 41% and 55% for the renovation baselines. In summer, heating is turned off and the temperatures during the night also can be lower than comfort limits pose. What is clearly visible in Figure 3.52, is that for the pre-renovation baselines, the amount of comfortable hours increases with the amount of construction elements that are retrofitted. Also, the renovation baselines clearly have a higher share of the time within the boundaries of comfort categories I and II because setpoint temperatures are reached faster when heating is turned on and temperatures decay slower.

Relative Humidity

For evaluating the relative humidity in the building, the same approach as for the thermal comfort is applied. The humidity is assessed for the whole building, and the concept of zone hours is used again. In this case, the relative humidity is analysed for the whole year and all climatised rooms, resulting in 140 176 zone hours.



	BS1_PB CS1_PB	BS2_PB CS1_PB	BS3_PB CS1_PB	BS1_RB CS1_RB	BS2_RB CS1_RB	BS3_RB CS1_RB
Above 70% - h	22444	22403	23262	9164	9163	8382
Between 30% & 70% - h	102066	102129	103106	108429	108957	110562
Below 30% - h	15666	15644	13808	22583	22056	21232
Above 70%	16%	16%	17%	7%	7%	6%
Between 30% & 70%	73%	73%	74%	77%	78%	79%
Below 30%	11%	11%	10%	16%	16%	15%

Figure 3.53 Relative humidity across baseline scenarios for MCT.

As can be seen in Figure 3.53, the relative humidity stays withing the 30% to 70% range most time of the year, indicating that indoor humidity is generally maintained within the recommended level. In the renovation baselines, it is clear that less zone hours above 70% relative humidity values are present, while the low humidity levels, below 30% RH, are more prevalent. This can be explained by the presence of a mechanical ventilation system that is removing the present moisture very effectively but also introduces a constant flow of dry air during winter.

CO_2 Concentration

The evaluation of indoor air quality (IAQ) is done by assessing the CO_2 concentrations in the building. For this parameter, not the whole building is assessed, but only two main rooms: the living room and the bedroom. This eliminates the need for using zone hours. Consequently ,the total amount of hours assessed is the total amount of hours in one year, namely 8760 hours.

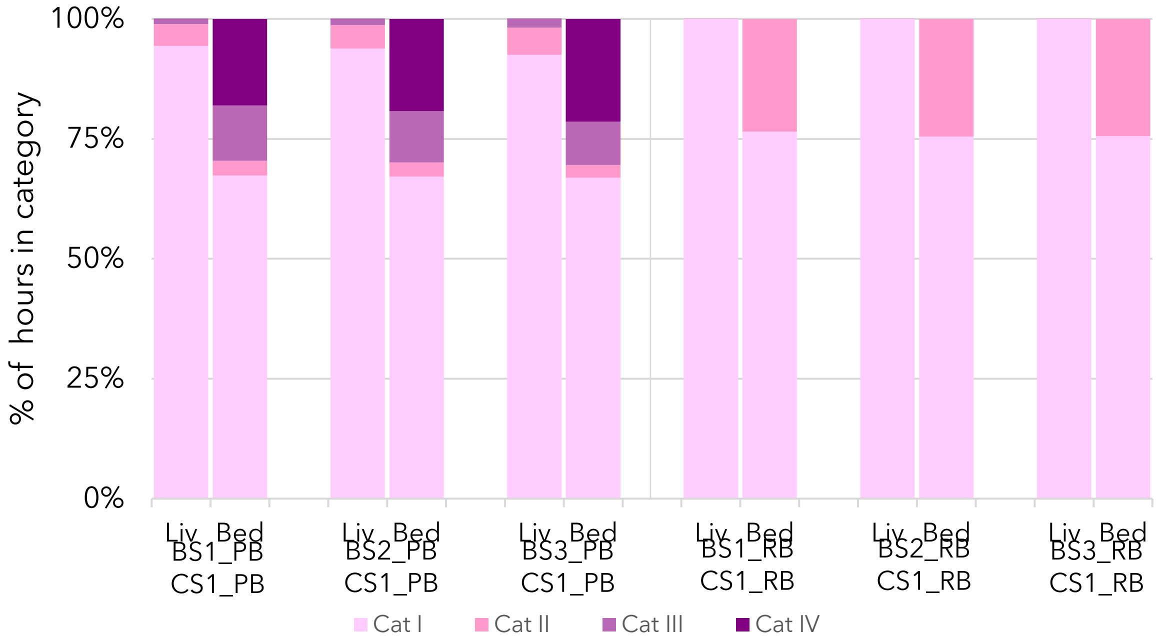


Figure 3.54 IAQ categories across baseline scenarios for the living room and main bedroom for MCT.

As can be observed in Figure 3.54, the simulated IAQ is generally very good in the middle-class townhouse. Regarding the living room, only a very small percentage (1-2%) of the time in case of the pre-renovation baselines, the IAQ is not sufficient (in Cat III of IV). When introducing a mechanical ventilation system, the IAQ falls completely within category I and is consequently sufficient all the time.

Regarding the bedroom, the IAQ is worse than in the living room for both the pre-renovation and renovation baselines. In the pre-renovation condition, in 30% of the year the IAQ is not sufficient. As expected, only relying on window opening and air infiltration is not sufficient in a bedroom where two people sleep. When introducing a mechanical ventilation system (in the renovation baselines), the IAQ is sufficient the whole year. About 24% of the year a IAQ category II is noted in the main bedroom.

For both rooms, it is important to note that every hour of the day is accounted for in the graph, also the times when no one is present in these rooms. For the bedrooms in general, the highest CO_2 concentration occur during the night when two persons produce a lot of CO_2. During the day, when no one is present, the CO_2 production approaches the outdoor background concentration, hence the large share of hours within IAQ category I and II.

3.2.4. Modest house

The modest house is the smaller version of the middle-class townhouse. The facade is usually less wide with a typical width of 5m. The modest house was the housing for the lower bourgeoisie, so the ornamentation was less pronounced. The facades are more sober, most of the time, only a plastered or brick façade with minimal decoration is present. The organisation principles of the middle-class townhouse are still present: rooms are arranged in an enfilade with a strict hierarchy: representative spaces at the front and more private ones in the back and higher up. In this archetype, there is no bel étage, nor a cellar with windows at street level. Only two levels are present, with a third one beneath the pitched roof, which was usually habited. Also in the modest house, massive masonry walls form the bearing structure of this archetype, with wooden floors as intermediate floors.

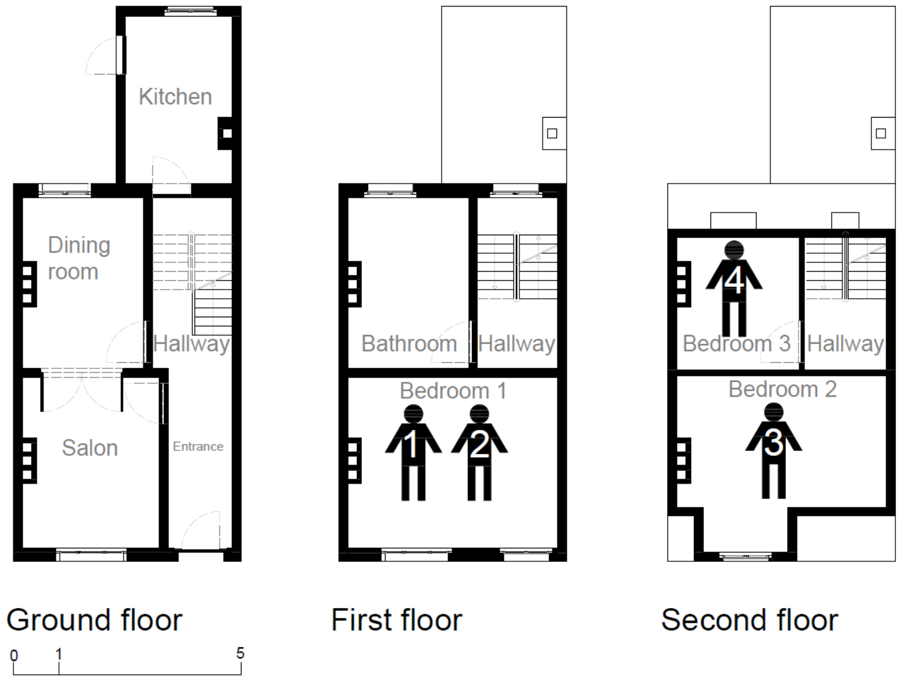


Figure 3.55 Overview of the pre-renovation baseline spatial organization of the MCT

For the pre-renovation baseline assessment, the living rooms are located on the ground floor and all the bedrooms and the bathroom are located on the upper floors (including on the attic level). The kitchen is in the small annex. The basement is not in use and consequently also not heated. A family of four people is assumed to inhabit this archetype, with the main bedroom on the first floor at the street side. Figure 3.55 gives an overview of the pre-renovation baseline.

For the renovation baseline, a change of the spatial layout of the ground floor is assumed. The original annex is replaced with a new extension extending the whole width of the plot. The new living room is moved into this new extension and the kitchen is moved to the street-side room on the ground floor. The other floors are unchanged. An overview of this layout is given in Figure 3.56.

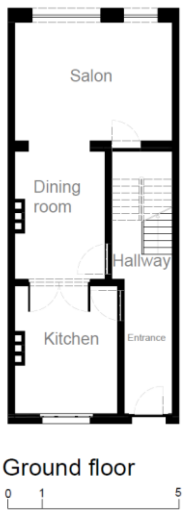


Figure 3.56 Overview of the renovation baseline spatial organization of the MCT

The archetype has a net heated surface of 110 m² and a net heated volume of 315 m³.

Results for pre-renovation and renovation baseline

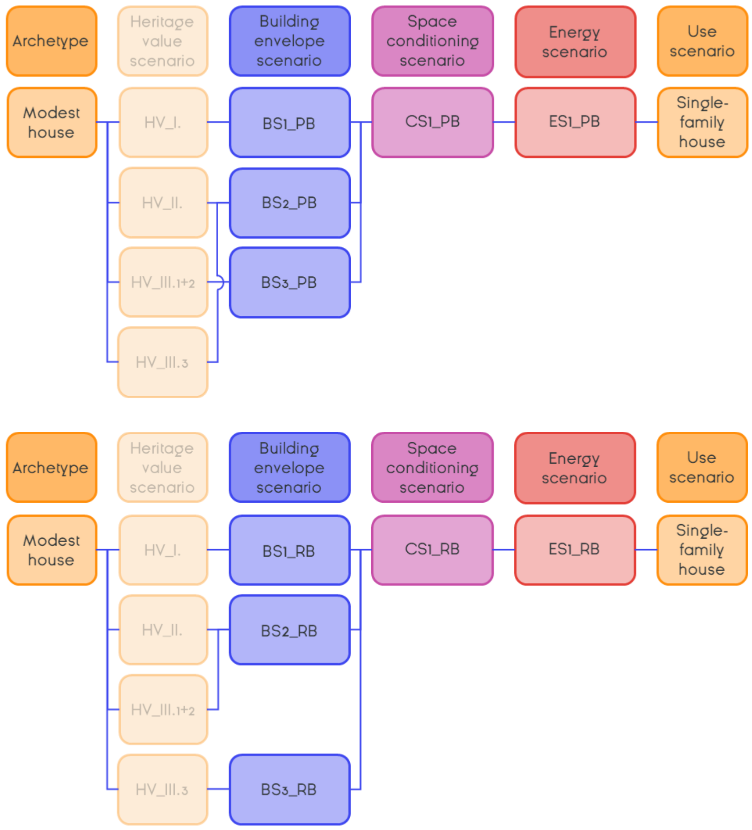


Figure 3.57 Overview of the pre-renovation (top) and renovation (bottom) baseline scenarios for the MH.

The modest house is modelled and simulated in different variations, as shown in Figure 3.57. For the simulations, the heritage value scenario is not influencing any of the results directly and is thus not a parameter.

Three different envelope scenarios are modelled for both the pre-renovation and the renovation baseline. The U-value of the different building envelope scenarios is provided in Table 3.14. Radiators with a thermostatic valve are the heat emission devices, with a central thermostat in the living room for the control of the heating system. For the new back-extension, a new radiator is assumed with a power of 1900 W at nominal conditions 75/65/20°C. Regarding the pre-renovation baseline, an old condensing gas boiler with a supply temperature of 90°C and a power of 20 kW is providing the space heating, electric boilers are providing the DHW supply. For the renovation baseline, a new condensing gas boiler with a power of 20 kW is providing for the space heating. A heating curve is applied, with a supply temperature of 75°C at an outdoor 6-hour moving average temperature of -8°C and a supply temperature of 20°C at an 6-hour moving average outdoor temperature of 20°C.

Modest house (MH)	Pre-renovation baseline (PB)			Renovation baseline (RB)		
U-value [W/m²K]						
Component	**BS1_PB**	**BS2_PB**	**BS3_PB**	**BS1_RB**	**BS2_RB**	**BS3_RB**
Exterior front facade	1.52	1.52	1.52	1.52	1.52	0.37
Exterior back facade	1.52	1.52	1.52	0.24	0.24	0.24
Interior bearing wall	1.69	1.69	1.69	1.69	1.69	1.69
Ground floor*	3.44	3.44	3.44	3.44	3.44	3.44
Interior floor	1.36	1.36	1.36	1.36	1.36	1.36
Flat roof	0.54	0.54	0.54	0.19	0.19	0.19
Pitched roof	0.72	0.72	0.72	0.22	0.22	0.22
*Only the construction elements and the heat transfer coefficient of the interior surface are taken into account.						
U-value glass [W/m²K]						
Front windows	5.8	5.8	2.8	1.9	1	1
Back windows	5.8	2.8	2.8	1	1	1
Airtightness						
v50 [m³/hm²]	16	14	12	8	6	6
Overall efficiency of technical systems						
η_{gen}	0.89	0.89	0.89	1.08	1.08	1.08
$\eta_{distr} * \eta_{distr}$	1	1	1	1	1	1

Table 3.14 Main information on U-values, airtightness and overall efficiency of the technical systems adopted in the different PB and RB baseline scenarios for the MCT.

For the renovation baseline, an idealised mechanical ventilation system with heat recovery is added with a constant heat recovery efficiency of 90%. The ventilation airflows are designed according to the Belgian national standard NBN D 50-001. Supply of fresh air is provided in the 'dry' rooms, extraction of air in the 'wet' rooms. An overview of the modelled ventilation flows are provided in Table 3.15. Slits beneath the doors of 2cm (or 2.5cm) are assumed to provide adequate flow of air between rooms.

Ventilation flows [m³/h]		
Room	Supply	Exhaust
Salon & Dining	93	
Kitchen		93
Bedroom 1	62	
Bathroom 1		159
Bedroom 2	62	
Bedroom 3	35	
Total	252	252

Table 3.15 Overview of the ventilation airflow design for the MH

Energy need

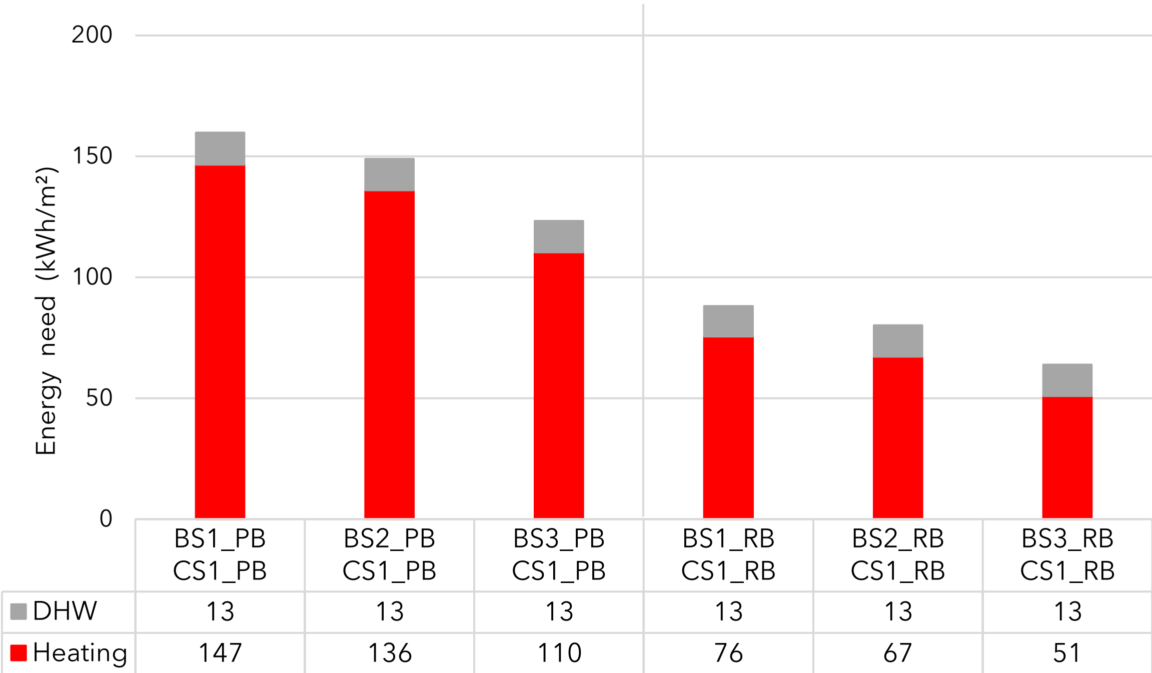
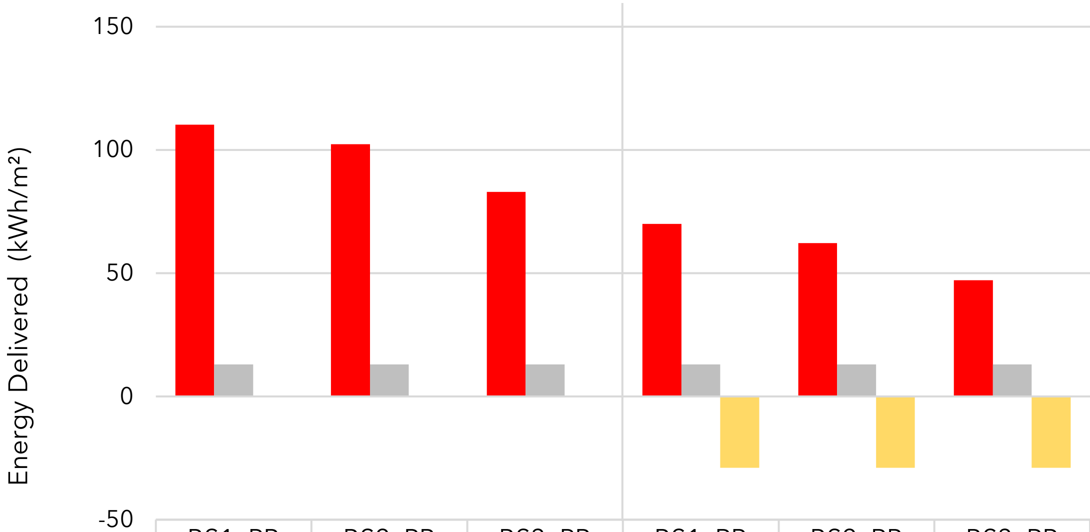


Figure 3.58 Energy need across baseline scenarios for MH.

The energy need results for the six different modest house archetype baseline are shown in Figure 3.58. The energy need in the modest house is lower than in the middle-class townhouses. While the MCT has more inhabitants, it also has more heated rooms, such as two bathrooms, a separate office and a veranda. The modest house is more compact, resulting in a lower overall energy need. Furthermore, the same trends as in the results of the middle-class townhouse can be observed: the energy need decreases with more elements being retrofitted and the renovation baseline scenarios have a smaller energy need than the pre-renovation baselines.

The relative share of DHW production in the energy need is larger than in the middle-class townhouse. The absolute amount of energy need for DHW doesn't vary a lot from that of the middle-class townhouse since this only depends on the number of occupants and there is only one inhabitant less for the modest house archetype baseline model.

Delivered energy

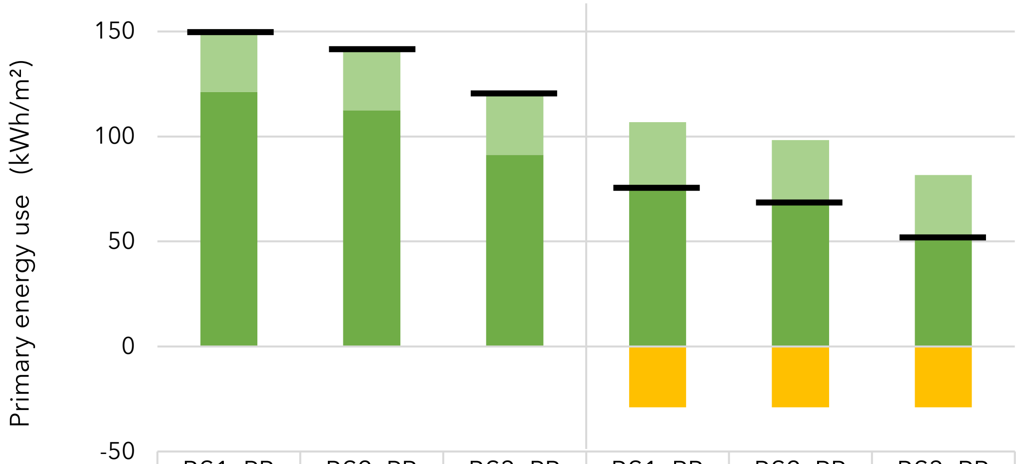


	BS1_PB CS1_PB	BS2_PB CS1_PB	BS3_PB CS1_PB	BS1_RB CS1_RB	BS2_RB CS1_RB	BS3_RB CS1_RB
Heating (gas)	110	102	83	70	62	47
DHW (electricity)	13	13	13	13	13	13
Solar energy	0	0	0	-29	-29	-29

Figure 3.59 Delivered energy across baseline scenarios for MH.

In general, also for the delivered energy the same trends can be observed as in the middle-class townhouse: the efficient condensing gas boilers causes the delivered energy to be lower for the renovation baselines. The solar energy production is relatively large compared to the delivered energy, compensating more than 60% of the space heating delivered energy in the best scenario (BS3_RB CS1_RB).

Primary energy use



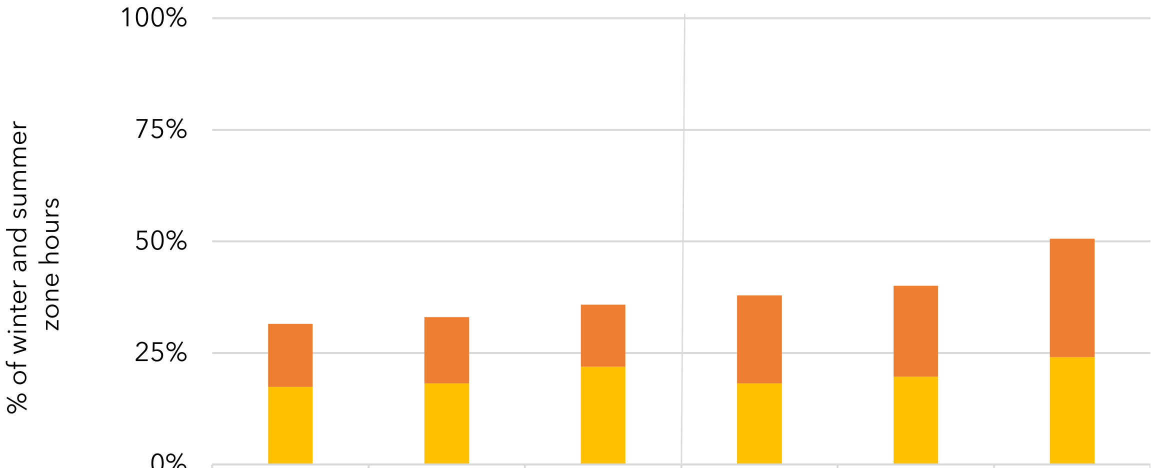
	BS1_PB CS1_PB	BS2_PB CS1_PB	BS3_PB CS1_PB	BS1_RB CS1_RB	BS2_RB CS1_RB	BS3_RB CS1_RB
Solar energy	0	0	0	-29	-29	-29
DHW	30	30	30	30	30	30
Heating	121	112	91	77	68	52
Net primary energy use		Net energy saving %		48%	54%	65%

Figure 3.60 Primary energy use across baseline scenarios for MH.

Also for the modest house, the primary energy use decreases when a whole building renovation is done, as illustrated in Figure 3.60. Again, BS3_RB CS1_RB is the best scenario with a primary energy use of 82 kWh/m² (excluding the benefit of solar energy). The energy generation from PV panels is 29 kWh/m², which causes the net primary energy use of the BS3_RB CS1_RB scenario to be 53 kWh/m². This is 65% lower than the worst pre-renovation scenario BS1_PB CS1_PB. In this case, the share of DHW production in the total primary energy use can be up to 37% of the total energy use (excluding the benefit of solar power generation). Although the building has undergone a thorough renovation, the DHW production system stays electric and because of this has a large impact on the overall result.

Thermal comfort

Thermal comfort is assessed for the whole building, by introducing the concept of zone hours (see MCT). The assessment is done for the winter period (Dec – Jan – Feb) and the summer period (Jun – Jul – Aug) separately. The basement is not taken into account, as it is not climatised. The total amount of zone hours for winter is 24288 and for summer 23760, totalling 48048 zone hours.



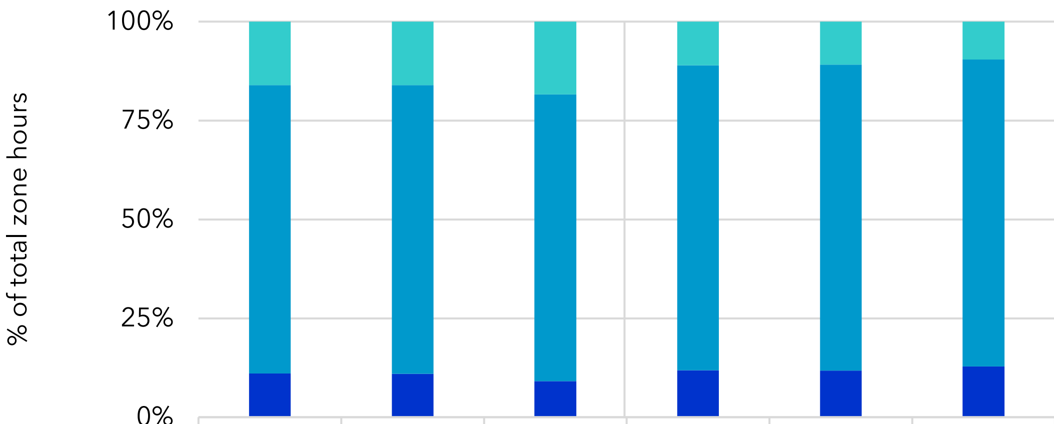
	BS1_PB CS1_PB	BS2_PB CS1_PB	BS3_PB CS1_PB	BS1_RB CS1_RB	BS2_RB CS1_RB	BS3_RB CS1_RB
Winter period - h	6784	7120	6679	9506	9798	12747
Summer period - h	8352	8732	10521	8720	9446	11571
Winter period %	14%	15%	14%	20%	20%	27%
Summer period %	17%	18%	22%	18%	20%	24%

Figure 3.61 Thermal comfort across baseline scenarios for MH. All zone hours within comfort category I and II are depicted.

The same trends as in the middle-class townhouse are observed in Figure 3.61: the more construction elements are replaced, the better the thermal comfort is. For the modest house, this is also the case for the renovation baselines. Also the renovation baselines score better regarding the thermal comfort. However, the renovation baseline BS1_RB CS1_RB has a lower summer comfort than the two of the pre-renovation baseline scenarios indicating a higher sensitivity for summer discomfort (overheating) issues.

Relative humidity

For evaluating the relative humidity in the building, the same approach as for the thermal comfort is applied. The relative humidity levels are assessed for the whole building, and the concept of zone hours is used again. In this case, the relative humidity is analysed for the whole year and all climatised rooms, resulting in 96371 zone hours.



	BS1_PB CS1_PB	BS2_PB CS1_PB	BS3_PB CS1_PB	BS1_RB CS1_RB	BS2_RB CS1_RB	BS3_RB CS1_RB
Above 70% - h	15448	15508	17705	10620	10485	9272
Between 30% & 70% - h	70285	70307	69874	74291	74513	74699
Below 30% - h	10638	10556	8792	11460	11373	12400
Above 70%	16%	16%	18%	11%	11%	10%
Between 30% & 70%	73%	73%	73%	77%	77%	78%
Below 30%	11%	11%	9%	12%	12%	13%

Figure 3.62 Relative humidity across baseline scenarios for MH.

For the modest house, the indoor humidity is most of the time within the acceptable levels. When mechanical ventilation systems are introduced, very high humidity levels occur less frequently, while low humidity levels become more common, as is also observed in the middle-class townhouse.

CO_2 Concentration

Data is available for all simulated zones but only two zones are assessed with regards to CO_2 concentrations and thus IAQ in this report: the living room and main bedroom. The total amount of hours assessed is the total amount of hours in one year, namely 8760 hours. As can be seen in Figure 3.63, the same trends as in the middle-class townhouse are present: for the pre-renovation baselines, most of the time the IAQ is within acceptable levels and when introducing mechanical ventilation, the IAQ is sufficient the whole year. The main bedroom performs worse than the living room. Noteworthy, BS3_PB CS1_PB has a worse IAQ than the other pre-renovation scenarios, both in the living room and bedroom. The better airtightness in this scenario causes a lower fresh air flow into the building.

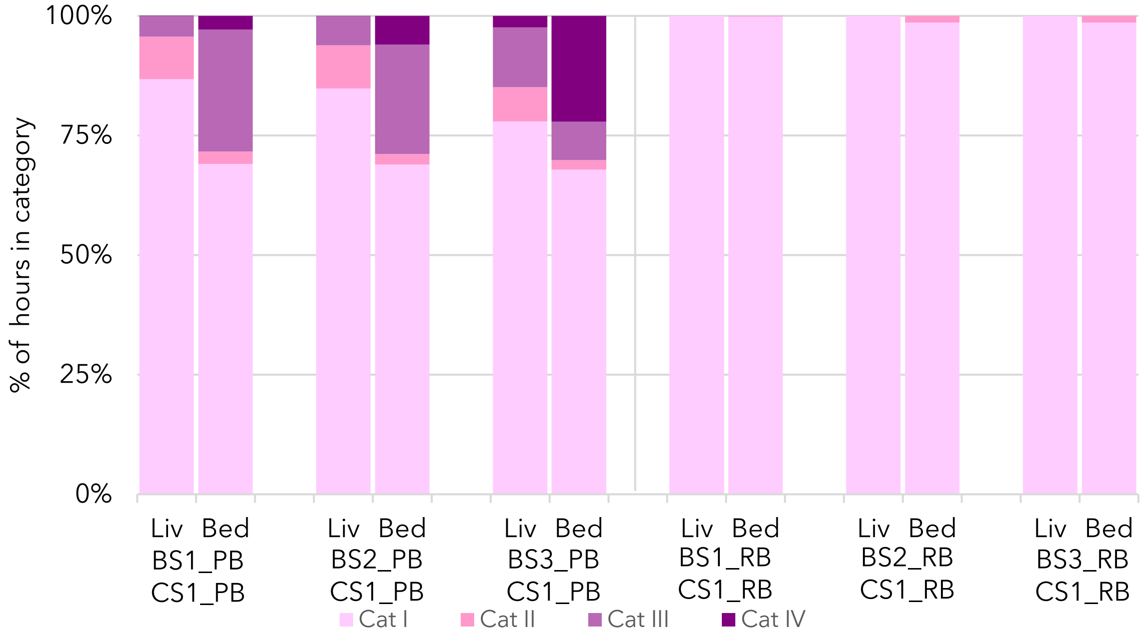


Figure 3.63 IAQ categories across baseline scenarios for the living room and main bedroom for MH.

3.2.5. Private mansion

The private mansion was the housing of the higher bourgeoisie, therefore this archetype is much larger and much more decorated. The typical width of the facade of the archetype is 11,5m and the expression of the façade is even more individualised and richly ornamented than the middle-class townhouse. The spatial organisation is different from that of the middle-class townhouse in that perspective that an additional span is present, as a result of which the circulation is placed centrally in the building, with a coach entry on the side. Further, the same principles as for the middle-class townhouse are present. Massive masonry walls form the bearing structure of this archetype, with wooden floors as intermediate floors.

For the baseline assessment, the organisation differs from the original setup of the building. A family of five people is assumed to inhabit this archetype, with the main bedroom being the bedroom on the first floor at the street side. The kitchen is located on the ground floor at the street side, the dining room at the back. A small TV room is located next to the kitchen, which is used by the occupants with a bedroom on the second floor. On the first floor, the actual salon is located at the street side, where the other occupants usually are located. On the second floor, an office is located. The basement and attic are not in use and consequently also not heated. The bathroom on the first floor is assumed to be used for the people who have bedrooms on that level. The same goes for the bathroom on the second floor. Figure 3.64 gives an overview.

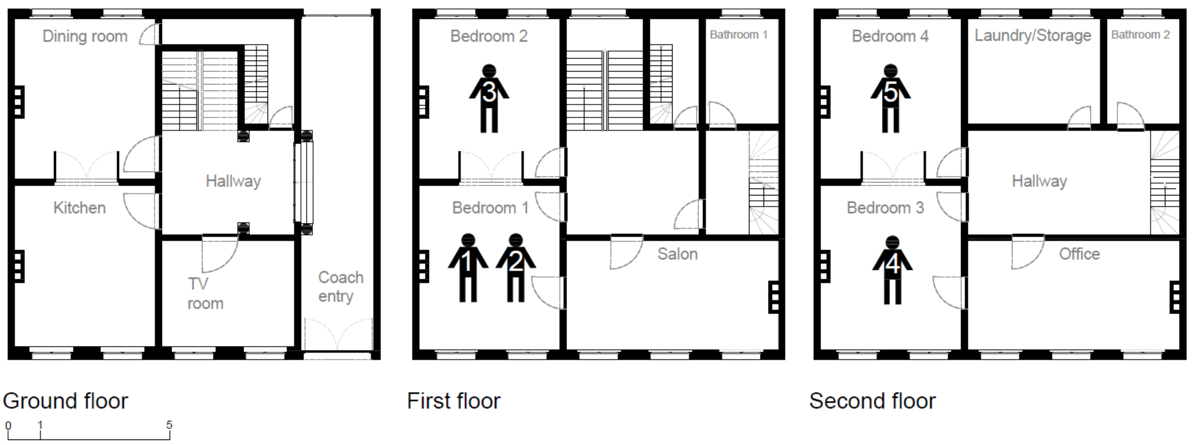


Figure 3.64 Overview of the baseline spatial organization of the PM.

The archetype has a net heated surface of 295 m² and a net heated volume of 1155 m³.

Results for pre-renovation and renovation baseline

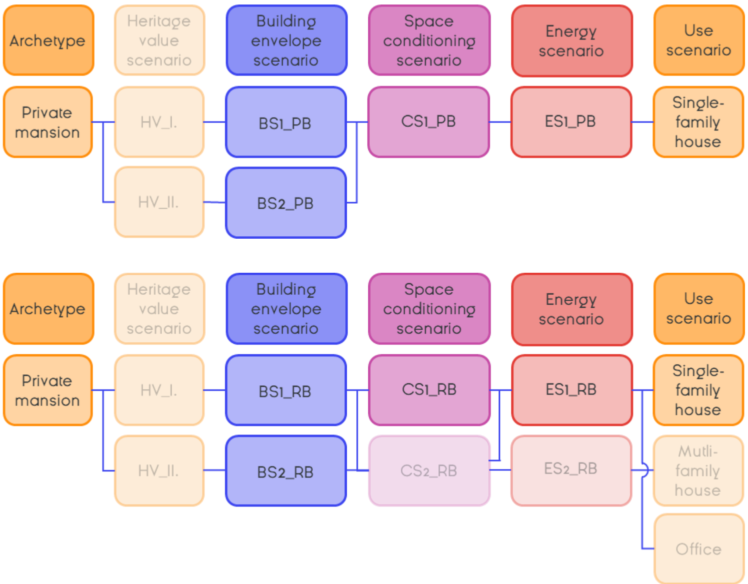


Figure 3.65 Overview of the pre-renovation (top) and renovation (bottom) baseline scenarios for the PM.

The private mansion is modelled and simulated in different variations, as shown in Figure 3.65. For this deliverable, the function of the renovation baseline is assumed to be the same as the pre-renovation baseline, a single-family house. The multi-family variant and the office are not assessed.

Two different envelope scenarios are modelled for both the pre-renovation and the renovation baseline are modelled. The U-value of the different building envelope scenarios are provided in Table 3.16. Radiators with a thermostatic valve are assumed, with a central thermostat for the heating system. Regarding the pre-renovation baseline, an old condensing gas boiler with a supply temperature of 90°C and a power of 60 kW is providing the space heating, electric boilers are providing the DHW supply. For the renovation baseline, a new condensing gas boiler with a power of 60 kW is providing for the space heating. A heating curve is applied, with a supply temperature of 75°C at an outdoor 6-hour moving average temperature of -8°C and a supply temperature of 20°C at an 6-hour moving average outdoor temperature of 20°C.

Private mansion (PM)	Pre-renovation baseline (PB)		Renovation baseline (RB)	
U-value [W/m²K]				
Component	**BS1_PB**	**BS2_PB**	**BS1_RB**	**BS2_RB**
Exterior front facade	1.52	1.52	1.52	1.52
Exterior back facade	1.52	1.52	0.24	0.24
Interior bearing wall	1.69	1.69	1.69	1.69
Ground floor*	3.44	3.44	3.44	3.44
Interior floor	1.36	1.36	1.36	1.36
Flat roof	0.54	0.54	0.19	0.19
Pitched roof	0.72	0.72	0.22	0.22
*Only the construction elements and the heat transfer coefficient of the interior surface are taken into account.				
U-value glass [W/m²K]				
Front windows	5.8	5.8	1.9	1
Back windows	5.8	2.8	1	1
Airtightness				
v50 [m³/hm²]	16	14	8	6
Overall efficiency of technical systems				
η_{gen}	0.89	0.89	1.08	1.08
$\eta_{distr} * \eta_{distr}$	1	1	1	1

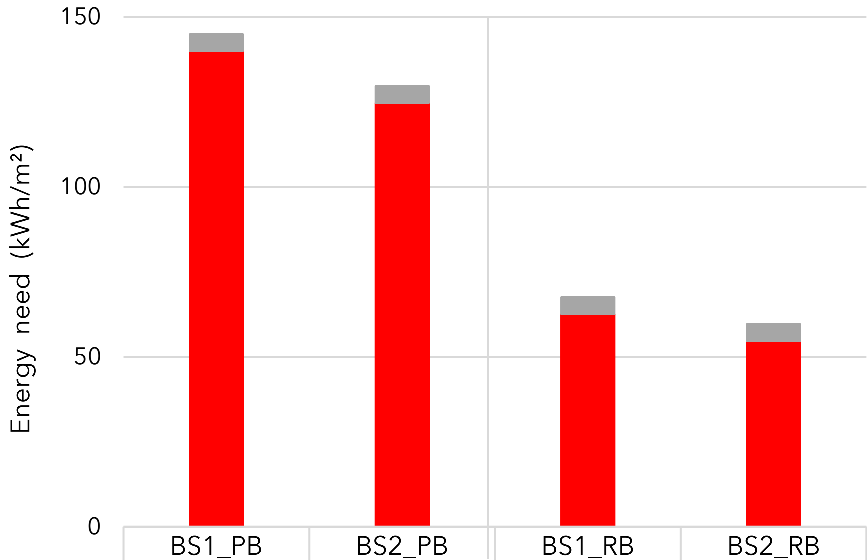
Table 3.16 Main information on U-values, airtightness and overall efficiency of the technical systems adopted in the different PB and RB baseline scenarios for the PM.

For the renovation baseline, a mechanical ventilation system with heat recovery is added with a constant heat recovery efficiency of 90%. The ventilation airflows are designed according to the Belgian national standard NBN D 50-001. Supply of fresh air is provided in the 'dry' rooms, extraction of air in the 'wet' rooms. An overview of the modelled ventilation flows are provided in Table 3.17. Slits beneath the doors between 2cm and 2.5cm are assumed to provide adequate flow of air between rooms.

Ventilation flows [m³/h]		
Room	Supply	Exhaust
Kitchen		200
Dining	77	
TV room	48	
Toilet (hallway)		53
Bedroom 1	72	
Bedroom 2	72	
Salon	78	
Bathroom 1		100
Bedroom 3	72	
Bedroom 4	72	
Office	72	
Bathroom 2		100
Storage/Laundry		100
Total	563	563

Table 3.17 Overview of the ventilation airflow design for the PM.

Energy need

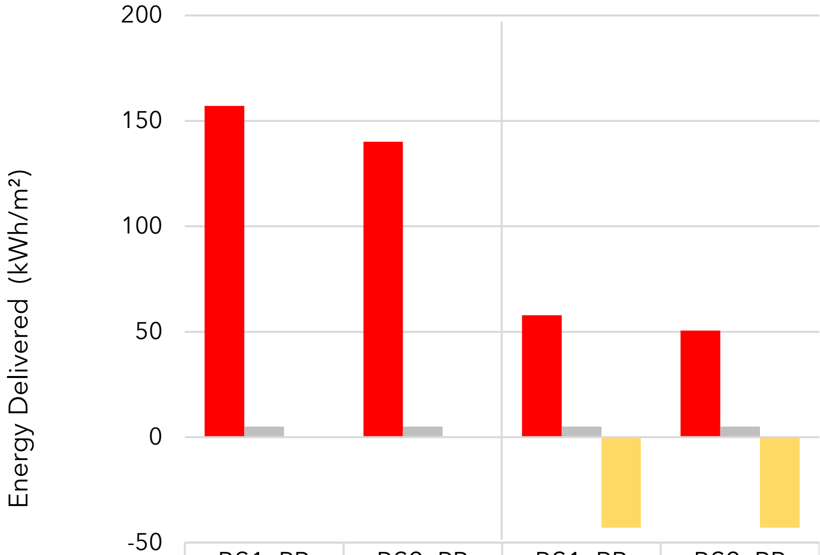


	BS1_PB CS1_PB	BS2_PB CS1_PB	BS1_RB CS1_RB	BS2_RB CS1_RB
DHW	5	5	5	5
Heating	140	125	62	55

Figure 3.66 Energy need across baseline scenarios for PM.

Figure 3.66 shows the energy need of the baselines of the private mansion. The normalised pre-renovation baseline energy need results are lower than the middle-class townhouse. This is mainly a consequence of the normalisation to surface area, which in this case benefits the larger dwelling. In absolute terms, the energy need can be more than 30% higher for the private mansion. The graph also clearly shows a reduction in energy need between pre-renovation and renovation baseline. Although only two scenarios for the pre-renovation baseline are compared, it is clear that replacing the back windows has a high impact on the energy need. The difference between the two renovation baselines is less pronounced. The share of energy need for production of DHW is small. In absolute terms, it is the same as in the middle-class townhouse, but normalization to the surface causes it to be much smaller.

Delivered energy

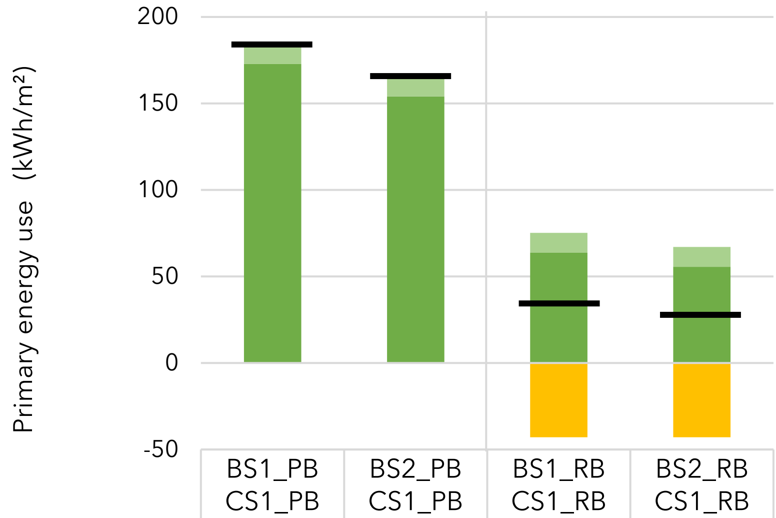


	BS1_PB CS1_PB	BS2_PB CS1_PB	BS1_RB CS1_RB	BS2_RB CS1_RB
Heating (gas)	157	140	58	51
DHW (electricity)	5	5	5	5
Solar energy	0	0	-43	-43

Figure 3.67 Delivered energy across baseline scenarios for PM.

As illustrated in Figure 3.67, the distinction between pre-renovation and renovation baseline is even more pronounced when assessing delivered energy, because of the introduction of efficient condensing gas boilers. A high amount of solar energy is generated because of the large roof available roof surface, which almost compensates for about 80% of the delivered energy.

Primary energy use



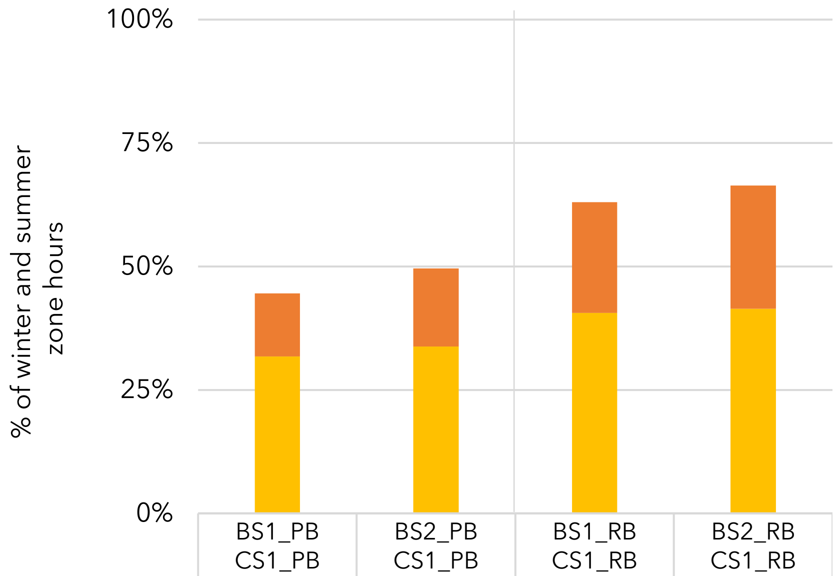
	BS1_PB CS1_PB	BS2_PB CS1_PB	BS1_RB CS1_RB	BS2_RB CS1_RB
Solar energy	0	0	-43	-43
DHW	12	12	12	12
Heating	173	154	64	56
Net primary energy use	Net energy saving%		83%	87%

Figure 3.68 Primary energy use across baseline scenarios for PM.

Figure 3.68 shows the same trends for the PM as in the previous archetypes: primary energy use decreases when a whole building renovation is undergone. BS2_RB CS1_RB is the best scenario and has a primary energy use (excluding the benefit of solar energy) of 68 kWh/m². The energy generation from PV panels is 44 kWh/m², which causes the net primary energy use of the BS2_RB CS1_RB scenario to be 25 kWh/m², which is 87% lower than the worst pre-renovation scenario BS1_PB CS1_PB and is reaching net zero primary energy use.

Thermal comfort

Thermal comfort is assessed for the whole building, by introducing the concept of zone hours (see middle-class townhouse). The assessment is done for the winter period (Dec – Jan – Feb) and the summer period (Jun – Jul – Aug) separately. The attic and basement are not taken into account, as they are not climatised. The total amount of zone hours for winter is 39744 and for summer 38880, totalling 78624 zone hours.



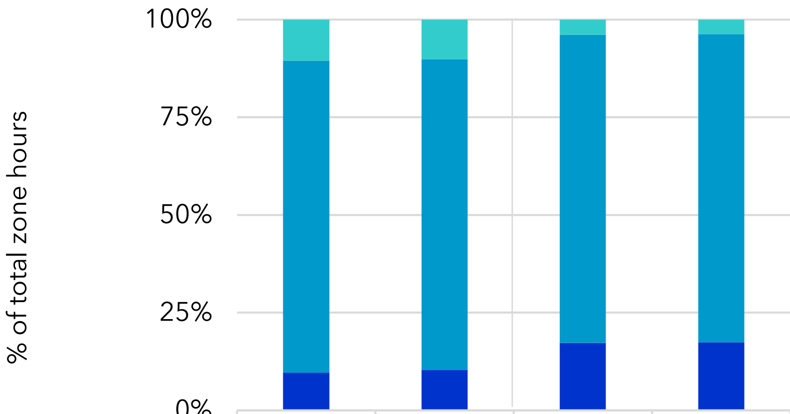
	BS1_PB CS1_PB	BS2_PB CS1_PB	BS1_RB CS1_RB	BS2_RB CS1_RB
Winter period - h	10055	12435	17617	19623
Summer period - h	24986	26560	31939	32594
Winter period %	13%	16%	22%	25%
Summer period %	32%	34%	41%	41%

Figure 3.69 Thermal comfort across baseline scenarios for MH. All zone hours within comfort category I and II are depicted.

In Figure 3.69, it is clear that for both the pre-renovation and the renovation baselines, the amount of comfortable hours increases with the amount of construction elements that are retrofitted. Also, the renovation baselines clearly have a higher share of the time within the boundaries of comfort categories I and II. For the summer period, a large share of the assessed period falls within the comfort bands of category II and II (up to 82% of summer).

Relative humidity

For evaluating the relative humidity in the building, the same approach as for the thermal comfort is applied. The humidity is assessed for the whole building, and the concept of zone hours is used again. In this case, the relative humidity is analysed for the whole year and all climatised rooms, resulting in 157 698 zone hours.



	BS1_PB CS1_PB	BS2_PB CS1_PB	BS1_RB CS1_RB	BS2_RB CS1_RB
Above 70% - h	16585	16109	6154	5841
Between 30% & 70% - h	125908	125276	124380	124317
Below 30% - h	15205	16313	27164	27540
Above 70%	11%	10%	4%	4%
Between 30% & 70%	80%	79%	79%	79%
Below 30%	10%	10%	17%	17%

Figure 3.70 Relative humidity across baseline scenarios for PM.

What is again illustrated in Figure 3.70, is that the relative humidity stays withing the 30% to 70% range most time of the year. What is more pronounced for the private mansion than for the middle-class townhouse, is the distinction between pre-renovation and renovation baseline. A larger share of the assessed period has a low humidity level, while only a very small share (4%) of the period knows a high humidity level. Since the rooms are generally larger but sources of humidity stay alike, the provided mechanical ventilation airflow from the ventilation system of the private mansion lower situations with high RH more but also introduces higher flow of dry air resulting in langer periods of dry RH.

CO_2 Concentration

Data is available for all simulated zones but only two zones are assessed with regards to CO_2 concentrations and thus IAQ in this report: the living room and main bedroom. The total amount of hours assessed is the total amount of hours in one year, namely 8760 hours. As can be seen on Figure 3.71, the same trends as in the previous archetypes are present: for the pre-renovation baselines, most of the time the IAQ is within acceptable levels and when introducing mechanical ventilation, the IAQ is sufficiently good the whole year. The main bedroom performs worse than the living room.

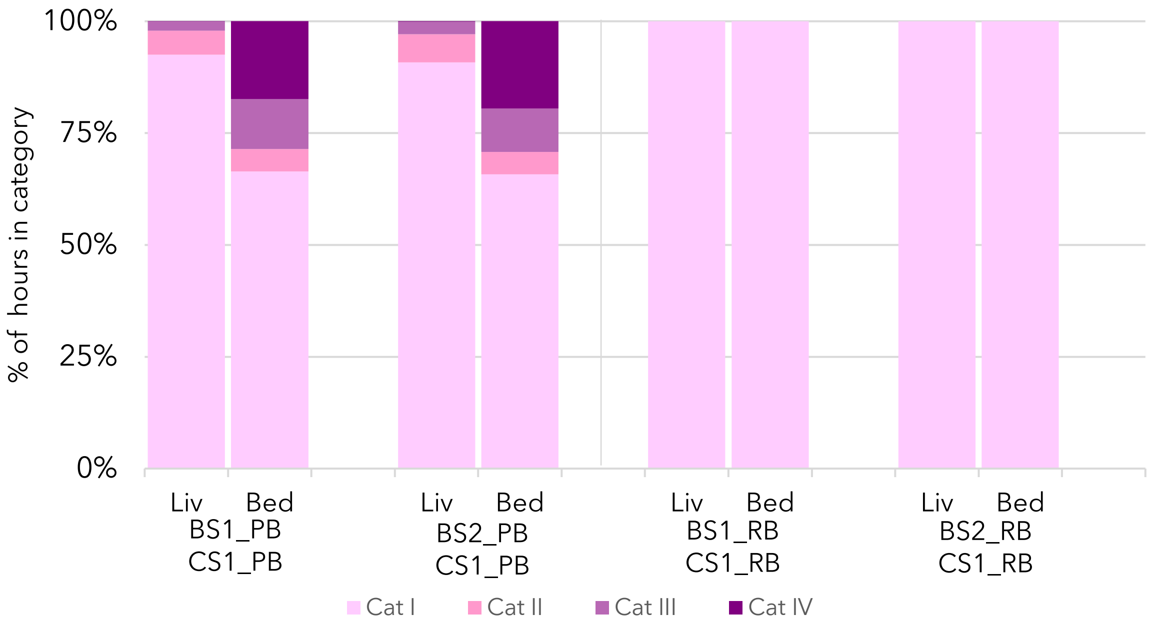


Figure 3.71 IAQ categories across baseline scenarios for the living room and main bedroom for PM.

3.2.6. Multi-family townhouse

The multi-family townhouse is the archetype that was originally conceived as a small-scale apartment building. The logic of the middle-class townhouse is transformed from a vertical organisation to a horizontal organisation. On each level, an apartments is present, which urges for a deeper building plot and an extension on each level. The typical width of the façade is 6m and the archetype has 4 levels, a cellar and an attic constructed with massive masonry walls and wooden intermediate floors.

A high number of assumptions had to be made regarding the spatial organisation of the apartments itself since less information was available on this topic for this archetype. The archetype is split up into 4 units: a larger one that covers the ground floor and the basement floor, and three smaller apartments on each of the other floors. The attic is assumed to be not in use, and consequently is not heated.

The larger apartment is habited by a family of three people. The kitchen, dining and salon are located on the ground floor, arranged from the street side to the back side. In the annex, an office is located. On the basement level, the main bedroom is located on the street side and the other bedroom at the back side, with a direct access to the garden. Inbetween, the bathroom is located.

Two people inhabit the first-level apartment, one person the second-level apartment and two people the third-level apartment. For these apartments, the arrangement of rooms is the same: at the street side, the kitchen and dining room are located. Behind, the salon is assumed, with the only bedroom located at the back side. The bathroom is located in the annex. Figure 3.72 gives an overview.

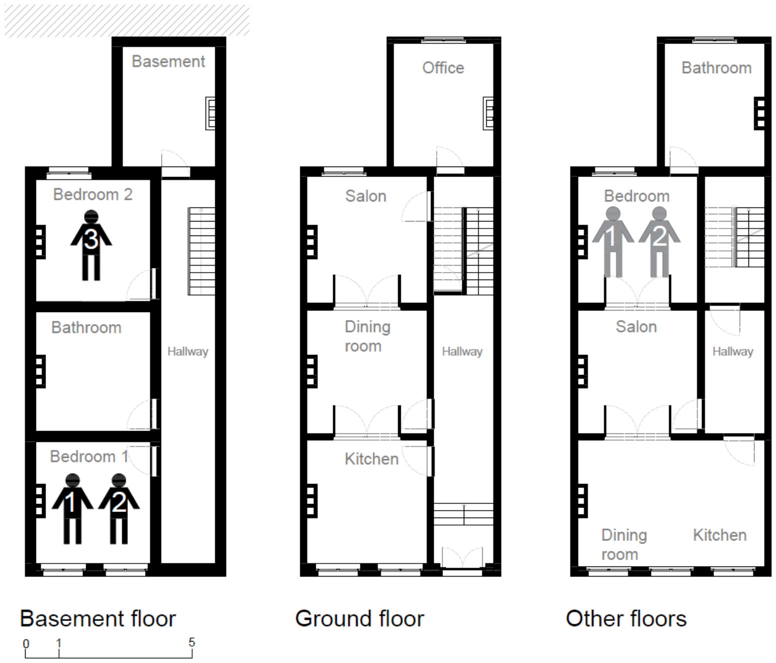


Figure 3.72 Overview of the baseline spatial organization of the MFT.

The archetype has a net heated surface of 350 m² and a net heated volume of 1125 m³. The ground-level apartment (including hallway) has a surface of 135 m² and a volume of 440 m³, the other apartments each have a surface of 72 m² and a volume of 225 m³.

Results for pre-renovation and renovation baseline

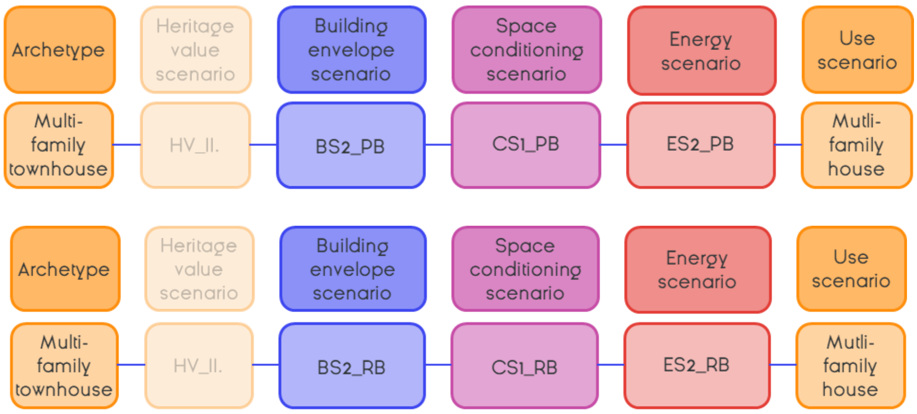


Figure 3.73 Overview of the pre-renovation (top) and renovation baseline (bottom) scenarios for the MFT.

The multi-family townhouse is modelled and simulated in only one variation for the pre-renovation baseline and one variation for the renovation baseline, as shown in Figure 3.73.

The envelope scenarios are shown in Table 3.18. Radiators with a thermostatic valve are assumed, with a central thermostat for the heating system. Regarding the pre-renovation baseline, an old condensing gas boiler with a supply temperature of 90°C is providing the space heating. Each apartment is equipped with their own boiler, with a power of 25 kW for the ground floor apartment, and 15 kW for the other apartments. Electric boilers are providing the DHW supply for the kitchen, the gas boiler for space heating is providing the DHW for the bathrooms. For the renovation baseline, a new condensing gas boiler is providing the space heating and DHW production for the bathroom. In this case, a heating curve is applied, with a setpoint for the supply temperature of 75°C at a 6-hour running average outdoor temperature of -8°C and a setpoint of 20°C at a 6-hour running average outdoor temperature of 20°C.

Multi-family townhouse (MFT)	Pre-renovation baseline (PB)	Renovation baseline (RB)
U-value [W/m²K]		
Component	**BS2_PB**	**BS2_RB**
Exterior front facade	1.52	1.52
Exterior back facade	1.52	0.24
Interior bearing wall	1.69	1.69
Ground floor*	3.44	3.44
Interior floor	1.36	1.36
Flat roof	0.54	0.19
Pitched roof	0.72	0.22
*Only the construction elements and the heat transfer coefficient of the interior surface are taken into account.		
U-value glass [W/m²K]		
Front windows	5.8	1
Back windows	5.8	1
Airtightness		
v50 [m³/hm²]	14	6
Overall efficiency of technical systems		
η_{gen}	0.89	1.08
$\eta_{distr} * \eta_{distr}$	1	1

Table 3.18 Main information on U-values, airtightness and overall efficiency of the technical systems adopted in the different PB and RB baseline scenarios for the MFT.

For the renovation baseline, a separate mechanical ventilation system with heat recovery (with an efficiency of 90%) is assumed for each apartment. The ventilation flows are designed according to the Belgian national NBN D 50-001. Supply of fresh air is provided in the 'dry' rooms, extraction of air in the 'wet' rooms. An overview of the ventilation flows are provided in Table 3.19. Slits beneath the doors of 2cm are assumed to provide adequate flow of air between rooms.

Ventilation flows [m³/h]		
Room	Supply	Exhaust
Apartment 0		
Kitchen & Salon	100	140
Office	40	
Bedroom 1	45	
Bedroom 2	45	
Bathroom		90
Total	230	230
Apartment 1,2,3		
Kitchen & Salon	100	100
Bedroom	50	
Bathroom		50
Total	150	150

Table 3.19 Overview of the ventilation airflow design for the MFT.

Energy need

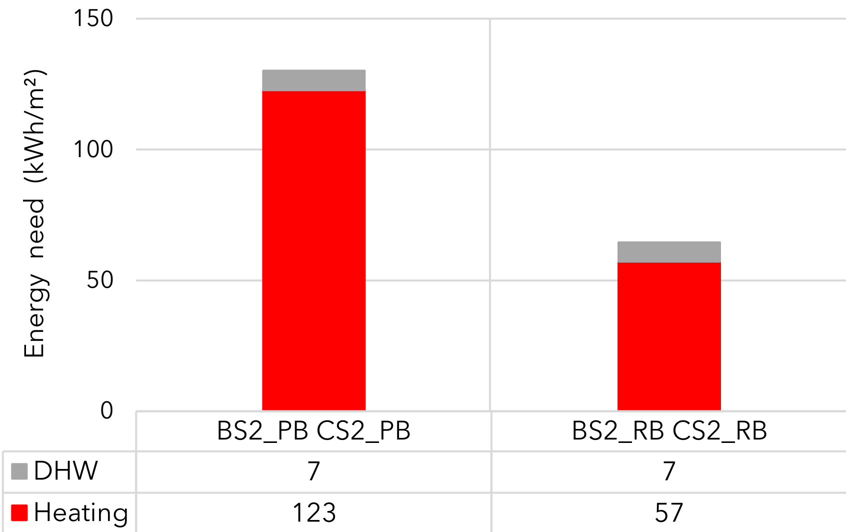
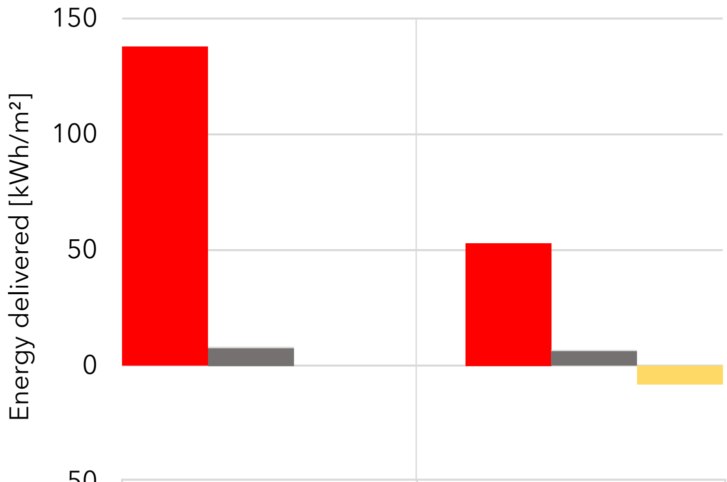


Figure 3.74 Energy need across baseline scenarios for MFT.

Figure 3.74 above clearly shows a reduction in energy use between pre-renovation and renovation baseline. The energy use per square meter is smaller than the energy use in all the other archetypes, again a consequence of the larger floor surface of this archetype compared to the heat loss area of the building (high compactness). In absolute terms of energy use, the multi-family townhouse uses more energy than the private mansion, however this is for an occupancy of eight people (in comparison of five people in the private mansion).

Delivered energy

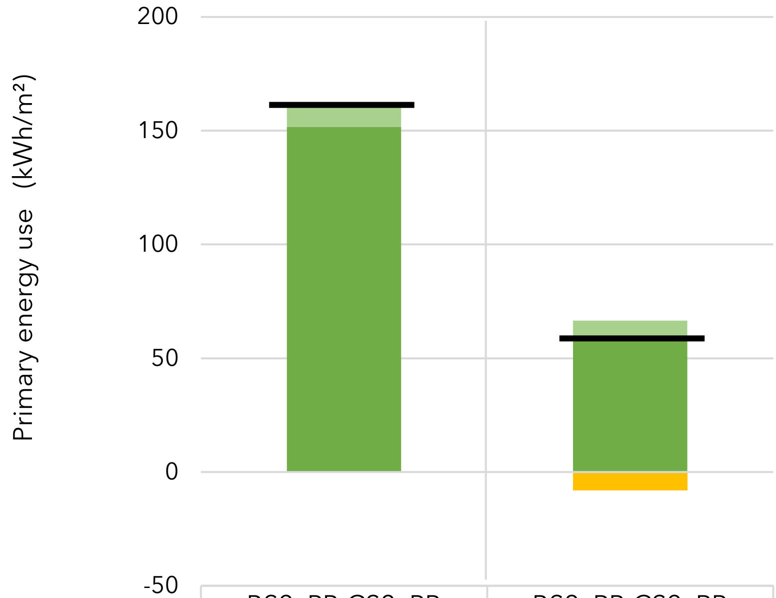


	BS2_PB CS2_PB	BS2_RB CS2_RB
Heating (gas)	138	53
DHW (gas)	8	6
DHW (electricity)	1	1
Solar energy	0	-8

Figure 3-75 Delivered energy across baseline scenarios for PM.

As is the case for the previous archetypes, the distinction between the pre-renovation and the renovation baseline is even larger when assessing the delivered energy, because of the more efficient condensing gas boilers in the renovation case. The difference in DHW delivered energy is also due to the more efficient gas boiler that is used to provide DHW in the bathrooms. The solar energy production is relatively limited, because of the small roof part that is available on this archetype. The mansard roof causes only one half of the roof section to be ideally inclined to put PV panels on.

Primary energy use



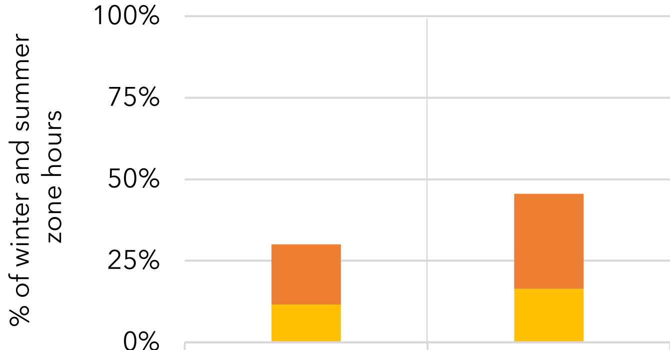
	BS2_PB CS2_PB	BS2_RB CS2_RB
Solar energy	0	-8
DHW	10	8
Heating	152	58
Net primary energy use	Net energy saving%	64%

Figure 3.76 Primary energy use across baseline scenarios for MFT.

For the multi-family townhouse, the whole building renovation decreases the primary energy use by more than half. The renovation baseline has a primary energy use (excluding the benefit of solar energy) of 66 kWh/m². The energy generation from PV panels is only 8 kWh/m², which causes the net primary energy use of the renovation baseline to be 58 kWh/m², which is 64% lower than the pre-renovation baseline. For the DHW production, a large share is provided by the gas boiler, with a low primary energy factor. But also a smaller part is provided by electric boilers, with a high primary energy factor.

Thermal comfort

Thermal comfort is assessed for the whole building, by introducing the concept of zone hours (see middle-class townhouse). The assessment is done for the winter period (Dec – Jan – Feb) and the summer period (Jun – Jul – Aug) separately. The attic is not taken into account, as it is not climatised. The total amount of zone hours for winter is 43200 and for summer 44160, totalling 87360 zone hours.



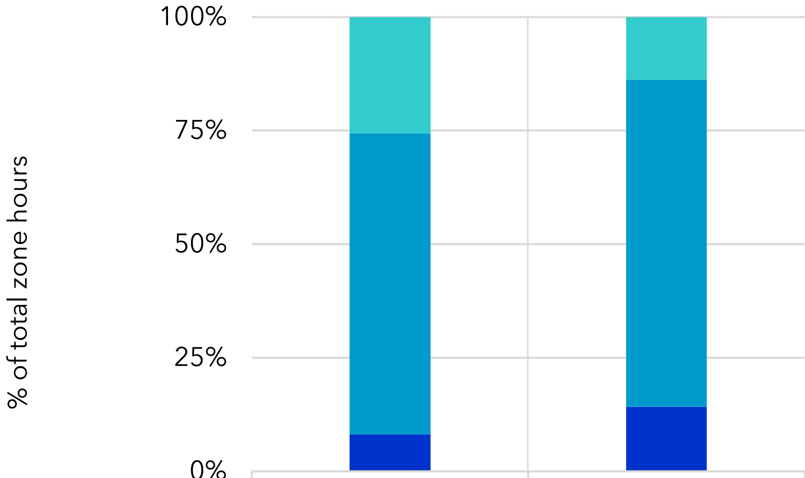
	BS2_PB CS2_PB	BS2_RB CS2_RB
Winter period - h	16083	25422
Summer period - h	10135	14334
Winter period %	18%	29%
Summer period %	12%	16%

Figure 3.77 Thermal comfort across baseline scenarios for MFT. All zone hours within comfort category I and II are depicted

The only trend that can be observed in Figure 3.77 is that the renovation baseline has a larger share of the assessed period falling between the comfort bands of category I and II. Mainly the winter comfort is improving when renovating the multi-family townhouse. Noteworthy, only a small share of the summer period falls within the comfort limits, the lowest of all archetypes.

Relative Humidity

For evaluating the relative humidity in the building, the same approach as for the thermal comfort is applied. The humidity is assessed for the whole building, and the concept of zone hours is used again. This time, the relative humidity is analysed for the whole year and all climatised rooms, resulting in 175 220 zone hours.



	BS2_PB CS2_PB	BS2_RB CS2_RB
Above 70% - h	44866	24130
Between 30% & 70% - h	116006	126158
Below 30% - h	14348	24932
Above 70%	26%	14%
Between 30% & 70%	66%	72%
Below 30%	8%	14%

Figure 3.78 Relative humidity across baseline scenarios for MFT.

For the multi-family townhouse, the indoor humidity is most of the time within the acceptable levels. When mechanical ventilation systems are introduced, high humidity levels occur less frequently, while low humidity levels become more common, as is also observed in the middle-class townhouse.

CO_2 Concentration

Only two zones are assessed in regards of CO_2 concentrations and thus IAQ: the living room and main bedroom of the ground level apartment. The total amount of hours assessed is the total amount of hours in one year, namely 8760 hours. As can be seen in Figure 3.79, the same trends as in the previous archetypes are present: for the pre-renovation baselines, most of the time the IAQ is within acceptable levels and when introducing mechanical ventilation, the IAQ is sufficiently good the whole year. Bedrooms perform worse than the living rooms: in the case of the multi-family townhouse, 40% of the year the IAQ of the bedroom is not sufficient in the pre-renovation baseline.

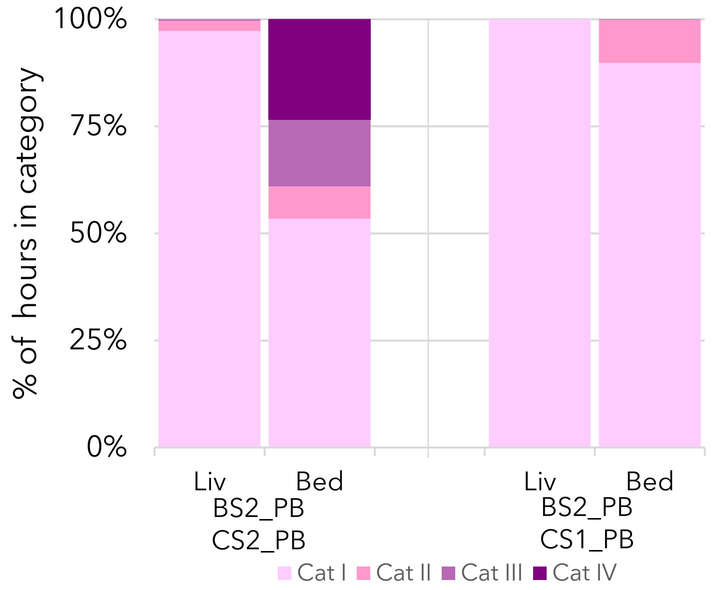


Figure 3.79 IAQ categories across baseline scenarios for the living room and main bedroom for MFT.

3.2.7. Lessons learnt

Based on the assessment of energy need, delivered energy, primary energy use, thermal comfort, relative humidity and IAQ across the different archetypes, it can be concluded that similar trends are present for all of them. The energy need, delivered energy and primary energy use consequently decreases when introducing a thorough renovation. The more building elements are retrofitted, the lower the energy need (and consequent indicators). The renovation scenarios of the renovation baselines ensure a decrease in primary energy use of almost 50% compared to the worst pre-renovation baseline for all archetypes. In several cases a decrease of more than 60% in noted. The solar power generation contributes further to this improvement (although its varying yield across the baselines). Note that the renovation baseline is not considering heritage restrictions such buildings might have and thus could be high-impact.

Regarding thermal comfort, all archetypes exhibit a higher proportion of time within comfort categories I and II under the renovation baselines, as setpoint temperatures are reached more rapidly and heat loss occurs more slowly. Furthermore, the number of comfortable hours increases with the extent of retrofitted construction elements in pre-renovation baselines. It is important to note that during nighttime setback periods, when heating setpoints are lowered, indoor temperatures fall outside comfort boundaries by design and are not necessarily problematic.

Notably, incorporating a mechanical ventilation system into the renovation baselines aligns with achieving a low energy demand, despite the additional heat losses compared to the pre-renovation baselines. Additionally, introducing the ventilation system ensures a better IAQ in the bedrooms across all archetypes compared to the pre-renovation baseline, where up to 40% of the zone hours the IAQ was not adequate. In the living room, IAQ was categorised most of the time into CAT II or better, even without mechanical ventilation systems. This indicates good airflow rates due to consistent window opening and a low airtightness.

Finally, the humidity levels in all the archetypes are generally between 30% and 70% most of the time, in both the pre-renovation and the renovation baselines. When introducing a mechanical ventilation system, the higher humidity levels are less prevalent and the low levels more prevalent, indicating a good removal of moisture but introduction of air which could be experienced as “too dry”.

3.3. Norway

The chosen archetype is the townhouse with courtyard, with a timber/wood log construction. Traditional log buildings in Norway hold significant cultural value.

The primary structure is made of massive wood, featuring either a wood log system or a system composed by vertical wooden planks within a timber frame. The prevailing construction is wood log system in the front buildings (towards the street), and either wood log or timber frame in the outbuildings (wing- and back yard buildings). More details of these two construction systems are described in the following chapters.

Main features of the archetype include four-room plan with courtyard, with unheated outbuilding, residential, two floors and attic under the roof.

3.3.1. General assumptions

Coupled BES-IAQ

The building models were created in the dynamic multi-zone building simulation software IDA ICE. IDA ICE was used to evaluate the annual energy use for heating, cooling and domestic hot water, as well as the thermal indoor climate.

Weather data

For model calibration, the outdoor temperature data from the nearest meteorological station were used as boundary conditions in order to reproduce the actual conditions during the monitoring period, while solar radiation data were taken from the university weather station.

For the Norwegian case studies in the final simulations, the official Norwegian Test Reference Year (TRY) climate file corresponding to Trondheim was used, which is the standard weather dataset applied in national building energy calculations.

Occupancy

For the Norwegian case study, a residential occupancy profile appropriate for apartment buildings was used. It was assumed that the use of dwellings is similar across neigh-bouring countries; therefore, the same occupancy profile as in the Estonian simulations was applied.

Heating and cooling

In the energy simulations, a heating setpoint temperature of 21 °C was applied for the occupied rooms. The setpoint is consistent with the indoor temperature measurements reported in Deliverable D3.2.

Occupancy related assumptions

The impact of occupants, such as the use of electrical appliances/artificial lighting, the use of DHW, etc., was considered in the model by defining some schedules for the various activities. The occupancy profiles and internal heat gains were implemented in accordance with the national building energy calculation methodology. Specifically, the following was considered for each parameter:

- Appliances & lighting: the heat gains from appliances and lighting is defined, both for convective as for radiative heat gains based on the specific profiles. The heat gain from appliances is calculated in relation to heated area using the occupied hours of 24 h and 7 days with usage rate of 16 hours and heat gain 1,8 W/m². The heat gain from lighting is calculated in relation to heated area using the occupied hours of 24 h and 7 days with usage rate of 16 hours and heat gain 1.95 W/m². Usage rate means the average use intensity of lighting and appliances during the building's occupied hours;

- Domestic hot water (DHW): in the calculations, the net heat demand for domestic hot water was assumed to be 29.8 kWh/m²·year, which is consistent with the standard usage profile for apartment buildings. These values were assumed to be constant throughout the year;

- In dynamic calculations, the heat gain from occupants is calculated in relation to heated area using the occupied hours of 24 h and 7 days with usage rate of 0.6 and heat gain 3 W/m³. Usage rate means the average presence of occupants during the building's occupied hours;

- Moisture production of activities: the latent loads from occupants (e.g. the moisture emitted by respiration and skin evaporation) are considered in the simulations through a moisture generation rate determined from the activity level assigned to each person and this water vapour is directly added into the zone's moisture balance. In such regard, the added vapour increases the humidity ratio and affects relative humidity, raising the latent cooling demand. The software continuously updates this moisture contribution during the simulation, so variations in occupancy or activity level directly influence the zone's latent loads;

- CO_2 production of activities: regarding CO_2 produced by people, a value of 20 l/h/person and 13.6 l/h/person was considered for awake and asleep people respectively, based on the specific profiles. CO_2 generation is based on occupant production rates for different activity levels according to EN 16798-1:2019.

Building context and obstructions

The buildings in the proximity of the case studies, both adjacent and opposite, were modelled considering their maximum volume to consider the shadows they generate. Similarly, other external shading elements such as eaves, dividing walls between properties, canopies, etc., which may affect the energy balance of the buildings, were also modelled. In the simulations, the case-study building was considered as a detached building on its plot, with no direct contact to neighbouring buildings; therefore, all external envelope elements are fully exposed and heat transfer is allowed through the entire external building envelope.

Thermal bridges

Thermal bridges were taken into account in the simulations by applying a normalized thermal bridge coefficient of 0.07 W/(m²K) per square metre of external envelope area.

Air infiltration

Infiltration was modelled by incorporating the air-tightness values defined in D5.4 for each scenario. The air leakage rate estimated at 50 Pa (m³/s·m²) was adjusted to the typical building pressure to reflect the specific airtightness of each case.

Multi-zone approach

Based on the multi-zone approach, each room of the building is treated as a separate zone, including both living spaces and hallways. Only the cellar and the attic are considered as single zone. This number of thermal zones for each archetype are shown in the following table.

Archetype	Number of zones
Wooden apartment building	6

Table 3.20 Number of zones in Norwegian archetype model

3.3.2. Wooden apartment building

The studied archetype is the **townhouse with courtyard**, which is characteristic of the "Bakklandet" neighbourhood of Trondheim. It is based on a timber/wood log construction.

Figure 3.80 Aerial view of the building surroundings and facade of the building

Results for Pre-renovation and Renovation baseline scenario

According to D5.4, the Pre-renovation baseline scenarios defined for the Norwegian archetype is shown in the scheme below.

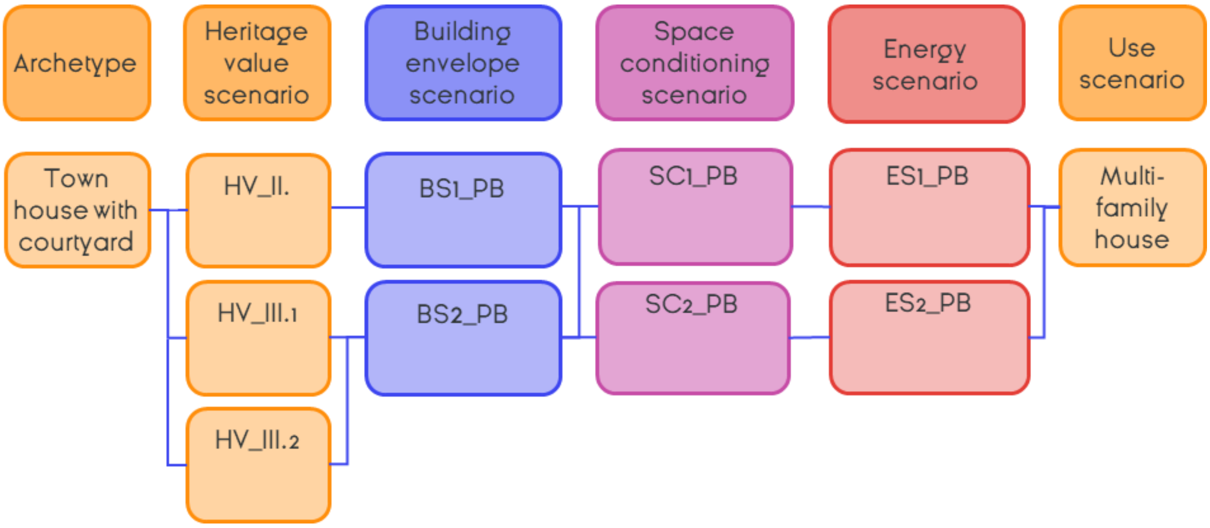


Figure 3.81 Overview of the Pre-renovation baseline scenarios for the Norwegian archetype

Similarly, based on D5.4, the Renovation baseline scenarios defined for the Norwegian archetype are shown in the scheme below.

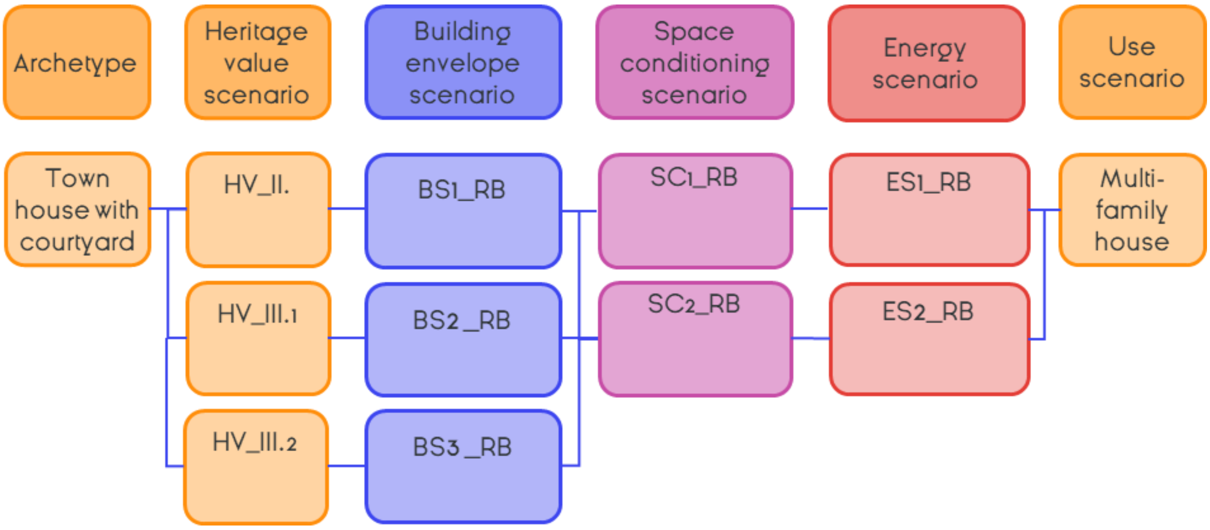


Figure 3.82 Overview of the Renovation baseline scenarios for the Norwegian archetype

The operational information has been implemented into the model to reflect the standard use of the building, as described in section 3.3.1. As far as the generation system is concerned, there are different systems considered to produce domestic hot water and heating. In the following tables are reported the U value for each building component, the air leakage rate qE50 and the overall efficiencies of the technical systems (η_{sys}) for the archetype analysed.

Pre-Renovation			Renovation		
U-Value [W/m²K]					
Compo-nent	Pre-reno, BS1_PB	Pre-reno, BS2_PB	Reno, BS1_RB	Reno, BS2_RB	Reno, BS3_RB

Exterior wall	1	1	0.54[1]	0.3	0.25
Internal wall	1	1	1	1	1
Ground floor	0.95	0.95	0.355	0.355	0.22
Interior floor	1	1	1	1	1
Attic floor	1	1	0.355	0.355	0.22
Roof					
Windows	1.5	1	1	1	0.85
Air Leakage Rate [m³/h·m²]					
q_{E50}	10		8	6.5	4
Overall efficiency of technical systems					
	Pre-Renovation		Renovation		
	ES1_PB	ES1_PB	*ES1_RB*	*ES2_RB*	
$\eta_{sys, heatsource}$	0.95		0.95		
$\eta_{sys, heat-system}$	0.9		0.9	0.88	
$\eta_{sys, DHW}$	0.98	0.98	0.98	0.98	
$\eta_{sys, cooling}$					
Ventilation [l/s·m²]					
$q_{vent, air flow}$	*nat*[2]		0.35		
$\eta_{sys, ventilation heat recovery}$	x		x		

[1] *weighted average*
[2] *nat – natural (air leakages + window airing converted into an equivalent ventilation airflow rate of 0.05 l/s·m²)*
[3] *airflow rate l/s per square metre of heated area*

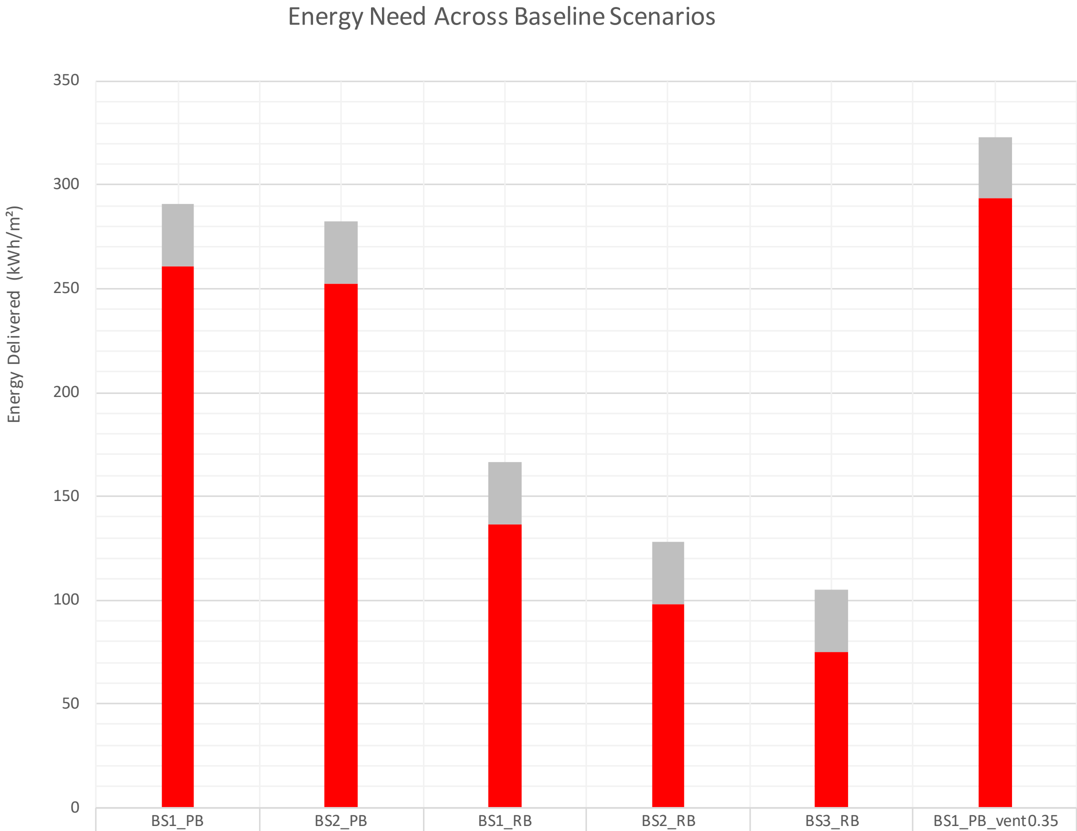
Table 3.21 Main information on U-value, Air Leakage Rate and Air change Rate for infiltration and overall efficiency of the technical systems adopted in the different Pre-renovation and Renovation baseline scenarios for the Wooden apartment Archetype

Following the estimation of the main output related to energy, comfort and IAQ aspects for each baseline scenario are presented.

The indoor climate graphs represent the conditions corresponding to the different insulation scenarios and changes in ventilation in the pre-renovation case. They do not coincide with the delivered and primary energy graphs, since the latter also reflect changes in the heat source and heating system.

Energy Need

Figure 3.83 shows the calculated annual energy need for space heating and domestic hot water (DHW) for the Norwegian case-study building under Trondheim TRY climate. The results are given for two pre-renovation baselines (BS1_PB and BS2_PB), three renovation baselines with progressively improved envelope performance (BS1_RB–BS3_RB), and one variant of the pre-renovation case with increased ventilation airflow (BS1_PB_vent0.35). The stacked columns display the contributions from space heating and DHW in kWh/m²·year. DHW demand is almost constant at about 30 kWh/m²·year in all scenarios, while space heating clearly dominates the total energy need.



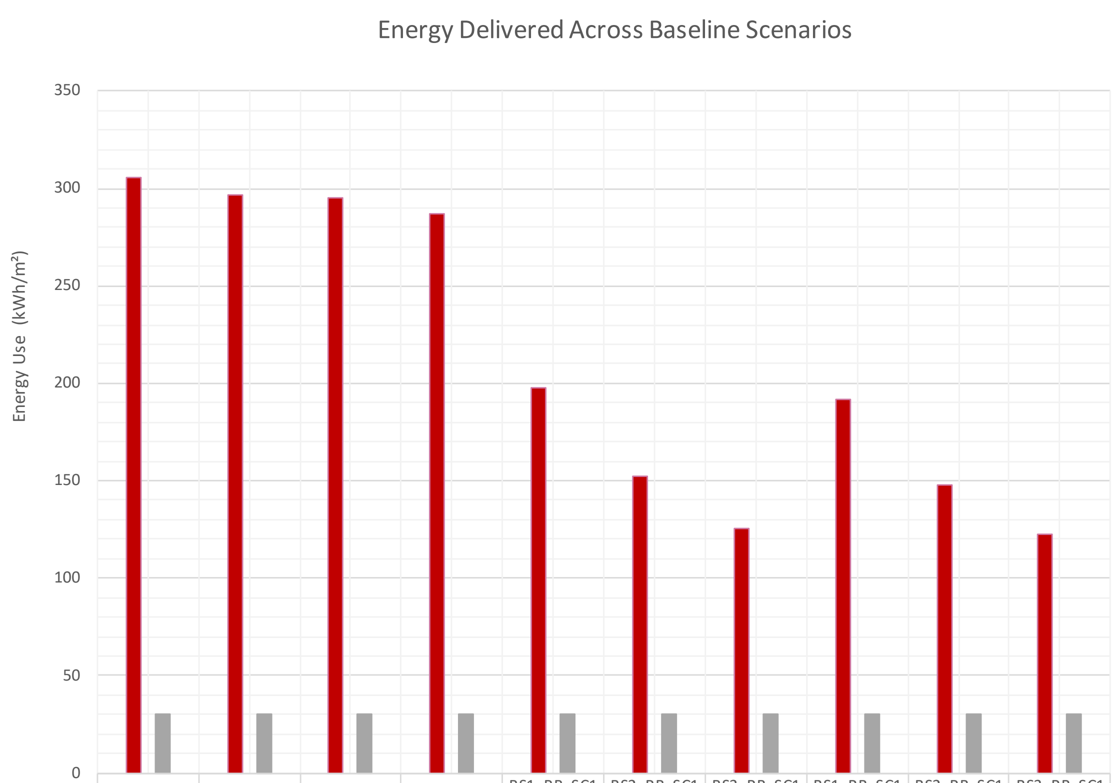
	BS1_PB	BS2_PB	BS1_RB	BS2_RB	BS3_RB	BS1_PB_vent0.35
DHW	29.8	29.8	29.8	29.8	29.8	29.8
Cooling						
Heating	261	253	136	98	75	294

Figure 3.83 Comparison of Energy Need (heating, cooling, and DHW) results for all baseline scenarios

The pre-renovation scenarios BS1_PB and BS2_PB have the highest heating needs, around 250–260 kWh/m²·year. Envelope renovation leads to a marked reduction: in BS1_RB, BS2_RB and BS3_RB the heating need decreases to 136, 98 and 75 kWh/m²·year respectively, corresponding to a reduction of roughly 50–70 % compared with the initial situation. The variant BS1_PB_vent0.35, where a higher ventilation airflow rate of 0.35 l/s·m² is applied to the pre-renovation envelope, exhibits the largest heating need (about 294 kWh/m²·year). This underlines the strong impact of ventilation losses in the cold Norwegian climate and shows that increasing ventilation without heat recovery can more than offset the savings obtained from moderate envelope improvements.

Energy Delivered

Figure 3.84 presents the *delivered* energy use for space heating and domestic hot water (DHW) for the Norwegian case-study building. In all scenarios, the heat supply is electricity-based: space heating is provided either by electric radiators, electric floor heating or water-based radiators supplied by an electric boiler, while DHW is also produced with electricity. Thus, the energy carrier remains the same and only small differences in system efficiencies and emission losses between these heating systems are taken into account. The grey part of each column represents DHW, which is constant at 30 kWh/m²·year in all cases, while the red part shows the delivered energy for space heating.



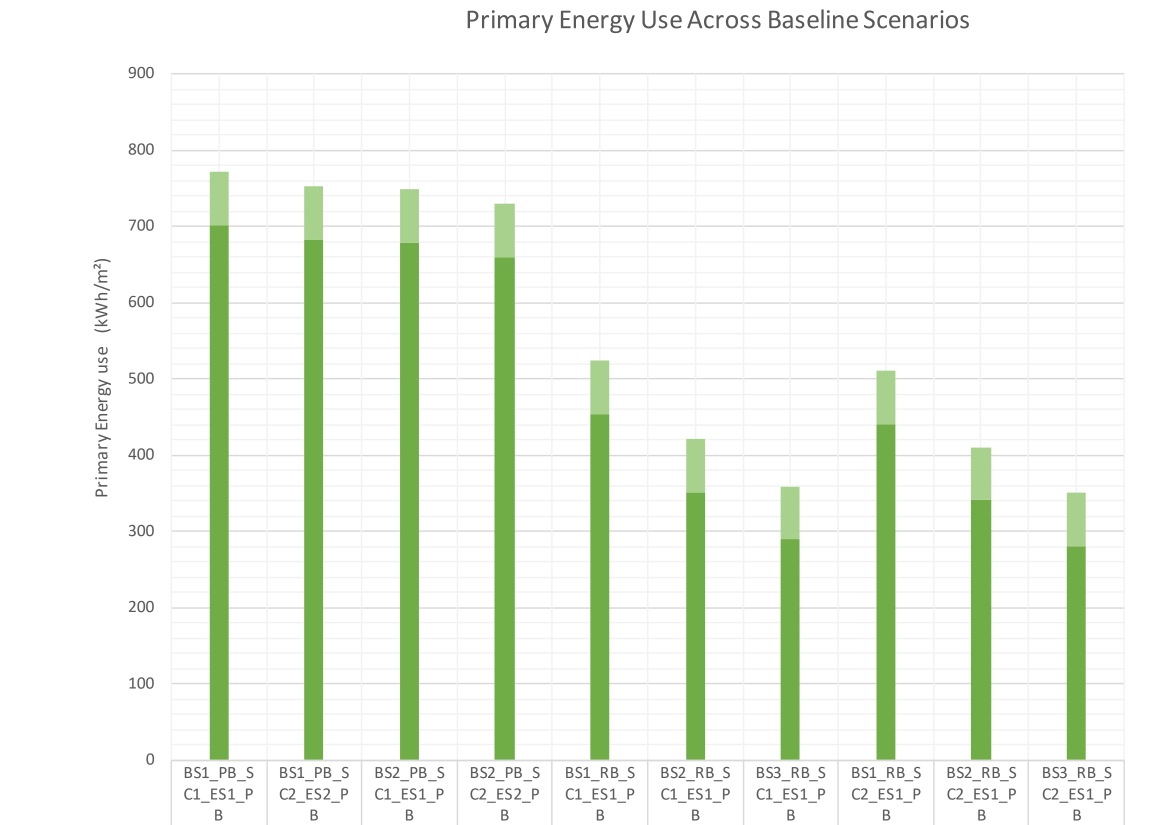
	BS1_PB_SC1_ES1_PB	BS1_PB_SC2_ES2_PB	BS2_PB_SC1_ES1_PB	BS2_PB_SC2_ES2_PB	BS1_RB_SC1_ES1_PB_vent0.35	BS2_RB_SC1_ES1_PB_vent0.35	BS3_RB_SC1_ES1_PB_vent0.35	BS1_RB_SC1_ES2_PB_vent0.35	BS2_RB_SC1_ES2_PB_vent0.35	BS3_RB_SC1_ES2_PB_vent0.35
Heating	305	297	295	287	197	152	126	192	148	122
Cooling	0	0	0	0	0	0	0	0	0	0
DHW	30	30	30	30	30	30	30	30	30	30

Figure 3.84 Comparison of Energy Delivered (heating, cooling, and DHW) results for all baseline scenarios. It should be noted that Energy Delivered for heating and DHW refers to thermal energy, while that for cooling refers to electrical energy

The pre-renovation scenarios (BS1_PB_SC1_ES1_PB and BS2_PB_SC2_ES2_PB) show the highest delivered heating energy, around 295–305 kWh/m²·year. Introducing higher ventilation airflow in the pre-renovation envelope (BS1_PB_vent0.35 and BS2_PB_vent0.35) leads to only minor changes in delivered energy, mainly reflecting the small efficiency differences between electric radiators, electric floor heating and water-based radiator systems supplied by an electric boiler. The renovation baselines (BS1_RB–BS3_RB with vent0.35) show a much more substantial decrease in delivered heating energy, down to about 120–200 kWh/m²·year. This reduction closely mirrors the trend observed for energy need and confirms that, in this set of scenarios with an unchanged electricity-based heat supply, improvement of the building envelope remains the dominant factor driving down delivered energy use.

Primary Energy Use

Figure 3.85 presents the primary energy use for space heating and domestic hot water (DHW) for the Norwegian case-study building. All scenarios rely on electricity both for space heating (electric radiators, electric floor heating or water-based radiators supplied by an electric boiler) and for DHW production, so the same primary-energy factor for electricity is applied throughout. The light-green part of each column represents DHW, which is constant at 70 kWh/m²·year, while the darker green part shows the primary energy use for space heating. The percentages below the columns indicate the reduction in primary energy compared with the corresponding pre-renovation case.

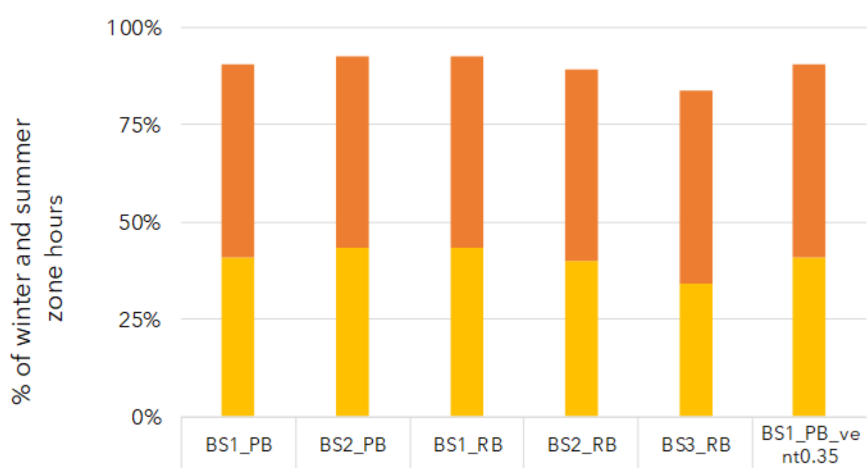


	BS1_PB_SC1_ES1_PB	BS1_PB_SC2_ES2_PB	BS2_PB_SC1_ES1_PB	BS2_PB_SC2_ES2_PB	BS1_RB_SC1_ES1_PB	BS2_RB_SC1_ES1_PB	BS3_RB_SC1_ES1_PB	BS1_RB_SC2_ES1_PB	BS2_RB_SC2_ES1_PB	BS3_RB_SC2_ES1_PB
DHW	70	70	70	70	70	70	70	70	70	70
Heating and cooling	702	683	679	660	454	351	289	441	341	281
Energy saving %	0%	3%	3%	5%	32%	46%	54%	34%	47%	55%

Figure 3.85 Comparison of Primary Energy (heating/cooling and DHW) results for all baseline scenarios. The percentage indicates the reduction in primary energy compared to the related pre-renovation scenario.

The pre-renovation scenarios (BS1_PB_SC1_ES1_PB and BS2_PB_SC2_ES2_PB) exhibit the highest primary energy use, around 750–770 kWh/m²·year. As the envelope is progressively renovated from BS1_RB to BS3_RB, primary energy use decreases substantially, with total values in the range 520–280 kWh/m²·year and savings of roughly 30–55 %. Because the energy carrier and its primary-energy factor remain unchanged, the pattern of primary-energy reduction closely follows the decrease in delivered energy: improvements in insulation and airtightness are clearly the dominant factors, while differences between the various electric heating systems only have a minor influence on the overall primary-energy results.

Thermal Comfort



	BS1_PB	BS2_PB	BS1_RB	BS2_RB	BS3_RB	BS1_PB_vent0.35
Winter period - h	4320	4320	4320	4320	4320	4320
Summer period - h	3575	3776	3776	3486	2990	3584
Winter period %	49%	49%	49%	49%	49%	49%
Summer period %	41%	43%	43%	40%	34%	41%

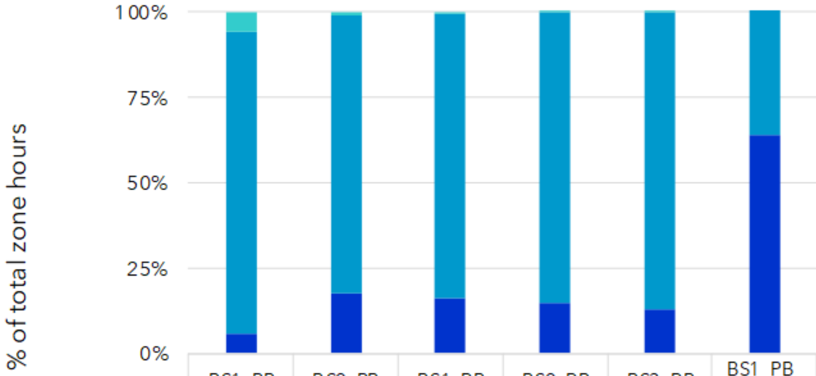
Figure 3.86 Comparison of Thermal Comfort (number of hours and % of time for winter and summer period inside CATII) results for all baseline scenarios

Figure 3.86 shows the share of winter and summer zone hours during which the operative temperature in the living room lies within the EN 16798-1 Category II comfort range, for all BS1 scenarios. The winter period accounts for about 4 320 h per year, while the summer period varies between roughly 3 000 and 3 800 h depending on the scenario.

Across all cases, around 49 % of the winter hours fall within Category II, with only minor differences between the pre-renovation (BS1_PB, BS2_PB), renovation (BS1_RB–BS3_RB) and increased-ventilation (BS1_PB_vent0.35) scenarios. This indicates that the heating system capacity is sufficient to maintain acceptable winter conditions even after the envelope is upgraded and the ventilation strategy is changed.

In summer, the picture is more sensitive to the renovation measures. In the pre-renovation scenarios (BS1_PB and BS2_PB) about 41–43 % of the summer hours are within the Category II band. As the envelope is progressively improved (BS1_RB → BS2_RB → BS3_RB), the fraction of hours within the comfort range tends to decrease, down to about 34 % in the best-insulated case BS3_RB. This reflects an increased tendency towards higher indoor temperatures in the well-insulated variants when no active cooling is provided. The variant BS1_PB_vent0.35 shows a summer comfort level similar to the reference BS1_PB, indicating that the change in ventilation rate alone has a limited effect on summer operative temperatures compared with the impact of envelope insulation.

Relative Humidity



	BS1_PB	BS2_PB	BS1_RB	BS2_RB	BS3_RB	BS1_PB_ vent0.35
Above 70% - h	509	103	43	22	12	50
Between 30% & 70% - h	7764	7126	7318	7446	7622	11887
Below 30% - h	489	1533	1401	1294	1128	5587
Above 70%	6%	1%	0%	0%	0%	1%
Between 30% & 70%	89%	81%	84%	85%	87%	136%
Below 30%	6%	17%	16%	15%	13%	64%

Figure 3.87 Comparison of Relative Humidity results for all baseline scenarios. The graph shows the number of hours and % of time inside the optimal range for RH (30-70%), below 30% of RH and above 70% of RH

Figure 3.87 presents the distribution of indoor relative humidity (RH) for the BS1 building state for all baseline and renovation scenarios. The results are shown as the share of total zone hours with RH below 30 %, between 30 % and 70 %, and above 70 %. The range 30–70 % is taken as the desirable comfort interval. In the pre-renovation reference case BS1_PB, indoor humidity is predominantly in the comfort range: about 89 % of all hours lie between 30 % and 70 % RH. Approximately 6 % of the hours exceed 70 % RH, and around 6 % are below 30 % RH, meaning that the base case exhibits occasional periods of both high and low humidity but remains acceptable for most of the time. The alternative pre-renovation case BS2_PB already shows fewer hours with high humidity (about 1 %), but the share of dry conditions increases to roughly 17 % of the hours. In the renovation baselines BS1_RB, BS2_RB and BS3_RB, hours with RH above 70 % are practically eliminated, and 81–87 % of the time remains within the comfort band. At the same time, the fraction of hours with RH below 30 % rises slightly compared to BS1_PB, to around 13–16 %, reflecting the combined effect of improved airtightness, higher internal temperatures and unchanged ventilation strategy. With increased ventilation in scenario BS1_PB_vent0.35, the high-humidity periods are almost completely removed. This clearly illustrates the drying effect of higher air exchange rates in a cold climate.

It should be noted that the simulations may not fully capture additional internal moisture loads observed in measurements. Nevertheless, the results indicate that increased ventilation is beneficial in situations with elevated moisture gains, as it reduces the risk of prolonged high RH levels that could become critical during colder periods, even though it also leads to a higher share of hours with low relative humidity.

CO_2 Concentration

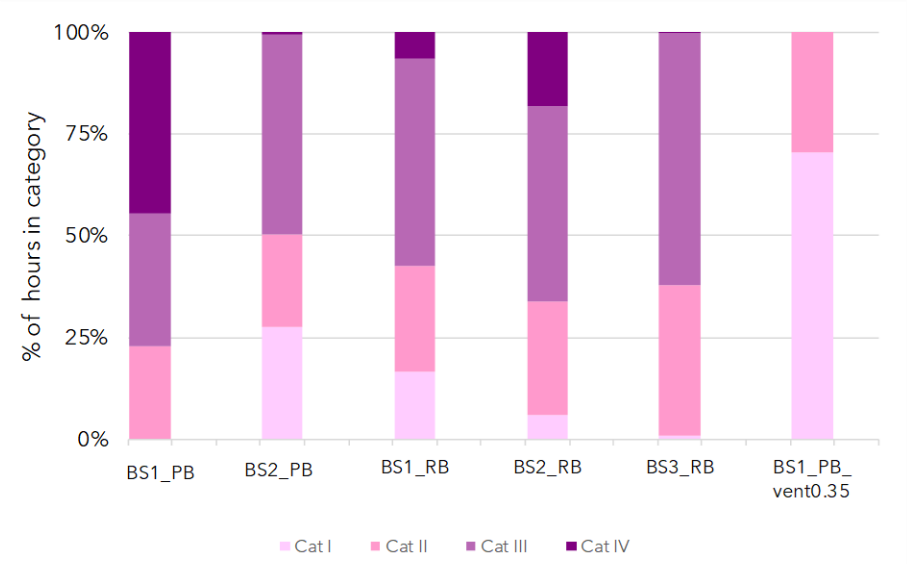


Figure 3.88 Distribution of CO_2 concentration levels for the BS1 scenarios

Figure 3.88 shows the distribution of indoor CO_2 concentration levels for the BS1 building state for all baseline and renovation scenarios. Results are expressed as the share of total zone hours in four categories (Cat I–IV), where Category I represents the lowest CO_2 concentrations (best air quality) and Category IV the highest CO_2 levels (poorest air quality).

In the reference case BS1_PB, indoor air quality is clearly unsatisfactory: 0 % of the hours are in Category I, only 24 % fall into Category II, while 39 % of the hours are in Category III and 37 % in Category IV. This means that around three quarters of the time CO_2 concentrations are in the two poorest categories, indicating frequent periods with inadequate ventilation. It should be noted that BS1_PB is calculated without any window opening for airing; therefore, the simulated CO_2 levels represent a worst-case situation compared with real use, where occupants are likely to open windows at least occasionally for ventilation. The alternative pre-renovation scenario BS2_PB provides slightly better air quality, with a larger share of hours in Categories I–II and fewer in Category IV, but Category III still dominates. In the renovation baselines BS1_RB, BS2_RB and BS3_RB, the distribution shifts gradually from Category IV towards Category III and partially Category II; nevertheless, a considerable fraction of time still remains in the two poorer categories, showing that envelope improvements alone do not guarantee good indoor air quality.

With increased ventilation in variant BS1_PB_vent0.35, the distribution changes fundamentally: about 70 % of the hours are in Category I and 30 % in Category II, while no hours occur in Categories III or IV. Thus, 100 % of the occupied time is spent in the two best air-quality categories, and periods with high CO_2 levels are completely removed.

3.3.3. Lessons learnt

The simulations confirm that the building envelope is the dominant lever for improving energy performance. Moving from the pre-renovation baselines to the three renovation baselines reduces the heating energy need by roughly 50–70 %, and the same pattern is reflected in delivered and primary energy, since all scenarios use electricity for both space heating and domestic hot water (DHW) with only minor differences in system efficiencies. The variant where the ventilation airflow is increased to 0.35 l/s·m² without changing the envelope shows the highest heating demand of all cases, illustrating how strongly ventilation losses affect energy use in the cold Trondheim climate and how quickly moderate envelope improvements can be offset if airflow is increased without heat recovery.

Because electricity is the sole energy carrier in all configurations, the reduction in primary energy closely follows the reduction in delivered energy. Overall, primary energy use decreases from around 750–770 kWh/m²·year in the pre-renovation state to roughly 280–520 kWh/m²·year in the best renovation scenarios, corresponding to savings of about 30–55 %. Differences between electric radiators, electric floor heating and water-based radiators supplied by an electric boiler have a comparatively small impact; their influence is clearly secondary to that of insulation level and airtightness. This indicates that, for this archetype, substantial energy and primary-energy savings can be achieved even without changing the energy carrier, provided that the envelope is renovated thoroughly and ventilation is well controlled. However, to achieve further reductions in primary energy, it would be necessary to consider alternative heat supply options with lower primary energy factors where available, such as a connection to an efficient district heating network.

The CO_2 analysis shows poor indoor air quality in the baseline scenario without increased ventilation. This should be interpreted as a conservative, worst-case condition, as occasional window airing by occupants is not represented in the simulations. When the ventilation rate is increased to 0.35 l/s·m², the distribution changes dramatically: approximately 70 % of the hours move into Category I and 30 % into Category II, and Categories III–IV disappear completely.

Overall, the Norwegian case study demonstrates that successful renovation of this heritage wooden townhouse typology requires a careful balance: robust envelope upgrades to limit heating and primary energy use, combined with adequately high – but well controlled – ventilation rates to secure good air quality, while managing the trade-offs related to increased heating demand and drier indoor air.

3.4. Estonia

In Estonia the project targets the neighbourhood of "Uus Maailm" in Tallinn. It is characterized by two heritage building archetypes: the wooden apartment building and the brick apartment building. The neighbourhood, archetype and case study building selection is further detailed in deliverable D5.1.

The wooden apartment building archetype has load-bearing walls made either of wooden logs or double plank type with ventilated cladding. The top boundary of the heated volume is usually the attic floor made of wooden lightweight beams with lightweight fillings or sand in between. The basement is unheated, and its ceiling is made of concrete slab, which may be supported by steel I-beams or railway rails within its volume. The foundation wall/plinth is made of limestone masonry which may or may not be plastered on the outside.

The brick apartment building archetype mainly differs from wooden one in the wall type (brick masonry with or without an air cavity) and due to that, also the inherently higher airtightness.

3.4.1. General assumptions

Coupled BES-IAQ

The building models were created in the dynamic multi-zone building simulation software IDA ICE. IDA ICE was used to evaluate the annual energy use for heating, cooling and domestic hot water, as well as the thermal indoor climate.

Weather data

For model calibration, the outdoor temperature measured on site at the Estonian case study buildings was used as boundary condition in order to reproduce the actual conditions during the monitoring period. For the other outdoor climate parameters (e.g. relative humidity, wind speed and solar radiation), measurements from the Tallinn weather station were used.

For the Estonian case studies in the final simulations, the Estonian test reference year (TRY) climate file was used, which is the standard weather dataset applied in national building energy calculations. The TRY climate file is derived from measured weather data for the period 1990–2020.

Occupancy

Due to the size and use of the buildings (apartment blocks), a typical residential occupancy profile for the apartment buildings was applied in both the calibration simulations and the baseline simulations. The assumed occupancy pattern is consistent with the standard profiles defined in the Estonian national methodology for building energy performance calculations.

Heating and cooling

In the energy simulations, a heating setpoint temperature of 21 °C was applied for the occupied rooms. Where active cooling was available, a cooling setpoint temperature of 27 °C was used during the summer period. These setpoints are consistent with the indoor temperature measurements reported in Deliverable D3.2 and are in line with the assumptions of the national building energy calculation methodology.

Occupancy related assumptions

The impact of occupants, such as the use of electrical appliances/artificial lighting, the use of DHW, etc., was considered in the model by defining some schedules for the various activities. The occupancy profiles and internal heat gains were implemented in accordance with the national building energy calculation methodology. Specifically, the following was considered for each parameter:

- Appliances & lighting: the heat gains from appliances and lighting is defined, both for convective as for radiative heat gains based on the specific profiles. The heat gain from appliances is calculated in relation to heated area using the occupied hours of 24 h and 7 days with usage rate of 0.6 and heat gain 3 W/m^3 (to obtain the electricity use of the appliances in residential buildings, the heat release value is divided by the factor 0.7). The heat gain from lighting is calculated in relation to heated area using the occupied hours of 24 h and 7 days with usage rate of 0.1 and heat gain 5 W/m^3. Usage rate means the average use intensity of lighting and appliances during the building's occupied hours;

- Domestic hot water (DHW): in the calculations, the net heat demand for domestic hot water was assumed to be 30 kWh/m^2·year, which is consistent with the standard usage profile for apartment buildings. The temperature difference between hot and cold water is taken to amount to 50°C. These values were assumed to be constant throughout the year;

- In dynamic calculations, the heat gain from occupants is calculated in relation to heated area using the occupied hours of 24 h and 7 days with usage rate of 0.6 and heat gain 3 W/m^3. Usage rate means the average presence of occupants during the building's occupied hours;

- Moisture production of activities: the latent loads from occupants (e.g. the moisture emitted by respiration and skin evaporation) are considered in the simulations through a moisture generation rate determined from the activity level assigned to each person and this water vapour is directly added into the zone's moisture balance. In such regard, the added vapour increases the humidity ratio and affects relative humidity, raising the latent cooling demand. The software continuously updates this moisture contribution during the simulation, so variations in occupancy or activity level directly influence the zone's latent loads;

- CO_2 production of activities: regarding CO_2 produced by people, a value of 20 l/h/person and 13.6 l/h/person was considered for awake and asleep people respectively, based on the specific profiles. CO_2 generation is based on occupant production rates for different activity levels according to EN 16798-1:2019.

Building context and obstructions

The buildings in the proximity of the case studies, both adjacent and opposite, were modelled considering their maximum volume to consider the shadows they generate. Similarly, other external shading elements such as eaves, dividing walls between properties, canopies, etc., which may affect the energy balance of the buildings, were also modelled. The case-study buildings themselves are located as detached buildings on their plots, with no direct contact to neighbouring buildings; therefore, all external envelope elements are fully exposed and heat transfer is allowed through the entire external building envelope.

Thermal bridges

Thermal bridges were taken into account in the simulations by applying linear thermal transmittance (ψ) values representative of the typical junctions in the studied building types.

Air infiltration

Infiltration was modelled by incorporating the air-tightness values defined in D5.4 for each scenario. The air leakage rate estimated at 50 Pa ($m^3/s \cdot m^2$) was adjusted to the typical building pressure to reflect the specific airtightness of each case.

Multi-zone approach

Based on the multi-zone approach, each room of the building is treated as a separate zone, including both living spaces and hallways. Only the cellar and the attic are considered as single zone. The number of thermal zones for each archetype is shown in the following table.

Archetype	**Number of zones**
Wooden apartment building	45
Brick apartment buildings	184

Table 3.22 Number of zones in each Estonian archetype model

3.4.2. Wooden apartment building

Those buildings are constructed of limestone (foundation and plinth), planks or wooden truss and bricks (stairwell). The facade can be covered in wooden boarding or with plaster. The roof type can be hip, jerkinhead, gambrel or mansard. The buildings have mostly two floors but for a short period also adding a third floor was allowed.

Figure 3.89 Aerial view of the building surroundings and facade of the building

Results for Pre-renovation and Renovation baseline scenario

According to D5.4, the Pre-renovation baseline scenarios defined for the Estonian archetypes are shown in the scheme below.

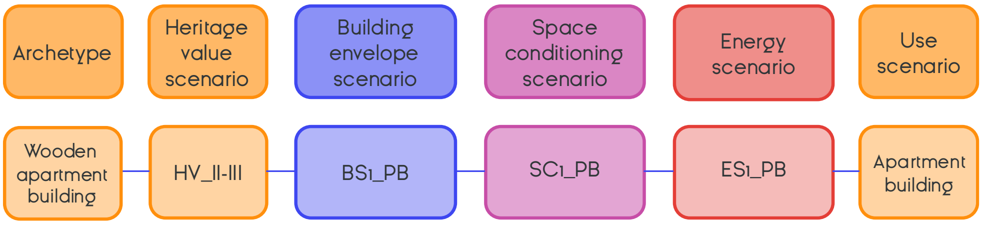


Figure 3.90 Overview of the Pre-renovation baseline scenarios for the Estonian archetypes

Similarly, based on D5.4, the Renovation baseline scenarios defined for the Estonian archetypes are shown in the scheme below.

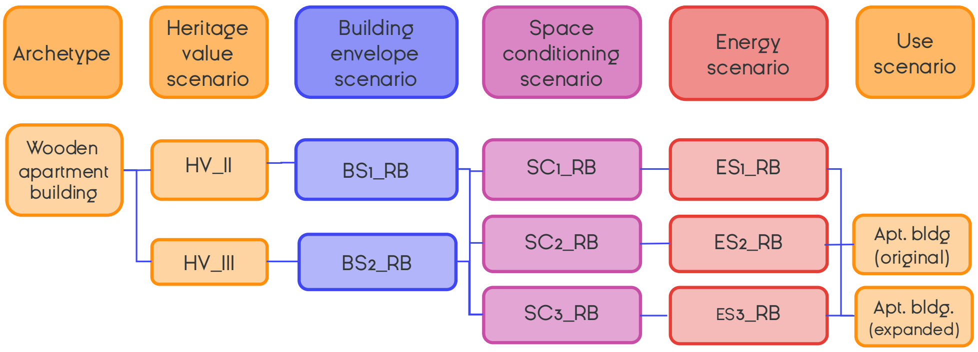


Figure 3.91 Overview of the Renovation baseline scenarios for the Estonian archetypes

The operational information has been implemented into the model to reflect the standard use of the building, as described in section 3.4.1. As far as the generation system is concerned, there are different systems considered to produce domestic hot water and heating. In the following tables are reported the U value for each building component, the air leakage rate qE50 and the overall efficiencies of the technical systems (ηsys) for the archetype analysed.

<table>
<tr><th colspan="3">Pre-Renovation</th><th colspan="5">Renovation</th></tr>
<tr><td colspan="8">U-Value [W/m²K]</td></tr>
<tr><td>Component</td><td colspan="2">Pre-reno, BS1_PB</td><td colspan="3">Reno, BS1_RB</td><td colspan="2">Reno, BS2_RB</td></tr>
<tr><td>Exterior wall</td><td colspan="2">1.12[1]</td><td colspan="3">0.99[1]</td><td colspan="2">0.85[1]</td></tr>
<tr><td>Internal wall</td><td colspan="2">1</td><td colspan="3">1</td><td colspan="2">1</td></tr>
<tr><td>Ground floor</td><td colspan="2">1</td><td colspan="3">1</td><td colspan="2">0.18</td></tr>
<tr><td>Interior floor</td><td colspan="2">0.9</td><td colspan="3">0.9</td><td colspan="2">0.9</td></tr>
<tr><td>Attic floor</td><td colspan="2">0.75</td><td colspan="3">0.25</td><td colspan="2">0.25</td></tr>
<tr><td>Roof</td><td colspan="2"></td><td colspan="3"></td><td colspan="2"></td></tr>
<tr><td>Windows</td><td colspan="2">2.9</td><td colspan="3">1.37[1]</td><td colspan="2">1.2</td></tr>
<tr><td colspan="8">Air Leakage Rate [m³/h·m²]</td></tr>
<tr><td>q_{E50}</td><td colspan="2">10</td><td colspan="3">9</td><td colspan="2">7</td></tr>
<tr><td colspan="8">Overall efficiency of technical systems</td></tr>
<tr><td></td><td colspan="2">Pre-Renovation</td><td colspan="5">Renovation</td></tr>
<tr><td></td><td>ES1_PB</td><td>ES1_PB</td><td>ES1_RB</td><td>ES1_RB</td><td>ES2_RB</td><td>ES2_RB</td><td>ES3_RB</td></tr>
<tr><td>$\eta_{sys, heatsource}$</td><td rowspan="2">0.75</td><td rowspan="2">0.75</td><td rowspan="2">0.75</td><td>0.9</td><td rowspan="2">0.75</td><td rowspan="2">3.5</td><td>0.9</td></tr>
<tr><td>$\eta_{sys, heat-system}$</td><td>0.97</td><td>0.97</td></tr>
<tr><td>$\eta_{sys, DHW}$</td><td>1</td><td>0.9</td><td>0.9</td><td>0.9</td><td>1</td><td>1</td><td>0.9</td></tr>
<tr><td>$\eta_{sys, cooling}$</td><td colspan="2">x</td><td>x</td><td>x</td><td>x</td><td>4.5</td><td>x</td></tr>
<tr><td colspan="8">Ventilation [l/s·m²]</td></tr>
<tr><td>$q_{vent, air flow}$</td><td colspan="2">nat[2]</td><td colspan="5">0.35</td></tr>
<tr><td>$\eta_{sys, ventilation heat recovery}$</td><td colspan="2">x</td><td colspan="5">x</td></tr>
<tr><td colspan="8">[1] weighted average
[2] nat – natural (air leakages + window airing converted into an equivalent ventilation airflow rate of 0.05 l/s·m²)
[3] airflow rate l/s per square meter of heated area</td></tr>
</table>

Table 3.23 Main information on U-value, Air Leakage Rate and Air change Rate for infiltration and overall efficiency of the technical systems adopted in the different Pre-renovation and Renovation baseline scenarios for the Wooden apartment Archetype

Following the estimation of the main output related to energy, comfort and IAQ aspects for each baseline scenario are presented.

The indoor climate graphs represent the conditions corresponding to the different insulation scenarios and changes in ventilation in the pre-renovation case. They do not coincide with the delivered and primary energy graphs, since the latter also reflect changes in the heat source and heating system.

Energy Need

Energy demand for heating, domestic hot water (DHW) and cooling across the baseline scenarios is presented in Figure 3.92. All values represent energy need at building level; system efficiencies and heat supply / distribution losses are not taken into account. Each stacked bar represents one scenario and shows the contribution of space heating (red), DHW (grey) and, where relevant, space cooling (blue) in kWh/m² of floor area. DHW demand is constant at 30 kWh/m² in all cases, while heating dominates the total delivered energy and varies roughly from about 55 to 155 kWh/m² between scenarios. Renovated cases generally show a substantially lower heating demand than the corresponding pre-renovation cases, except when mechanical ventilation is added. Cooling demand appears only in a few ventilated renovation scenarios and remains small (about 7 kWh/m²), so its impact on the total delivered energy is minor compared to heating.

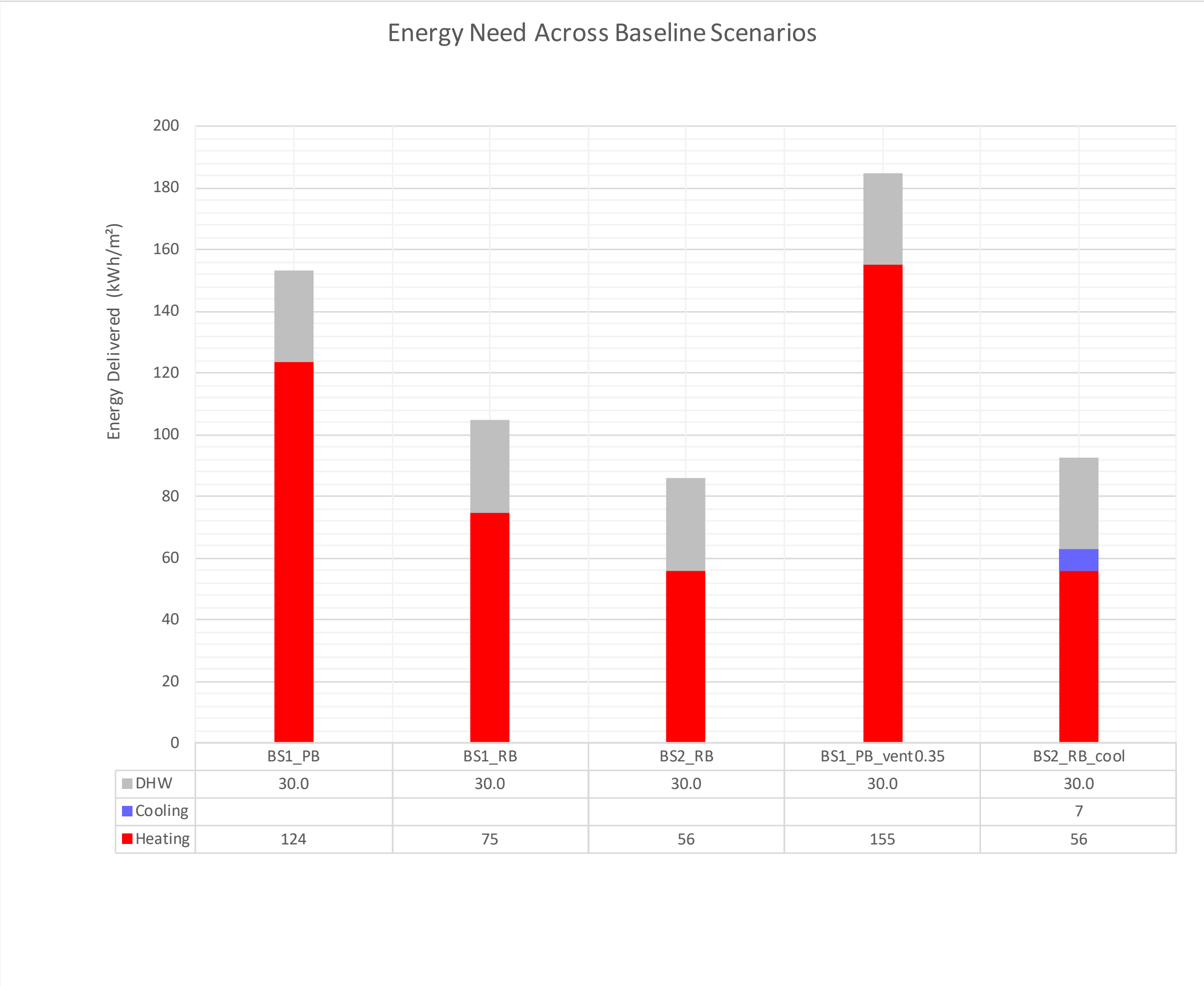
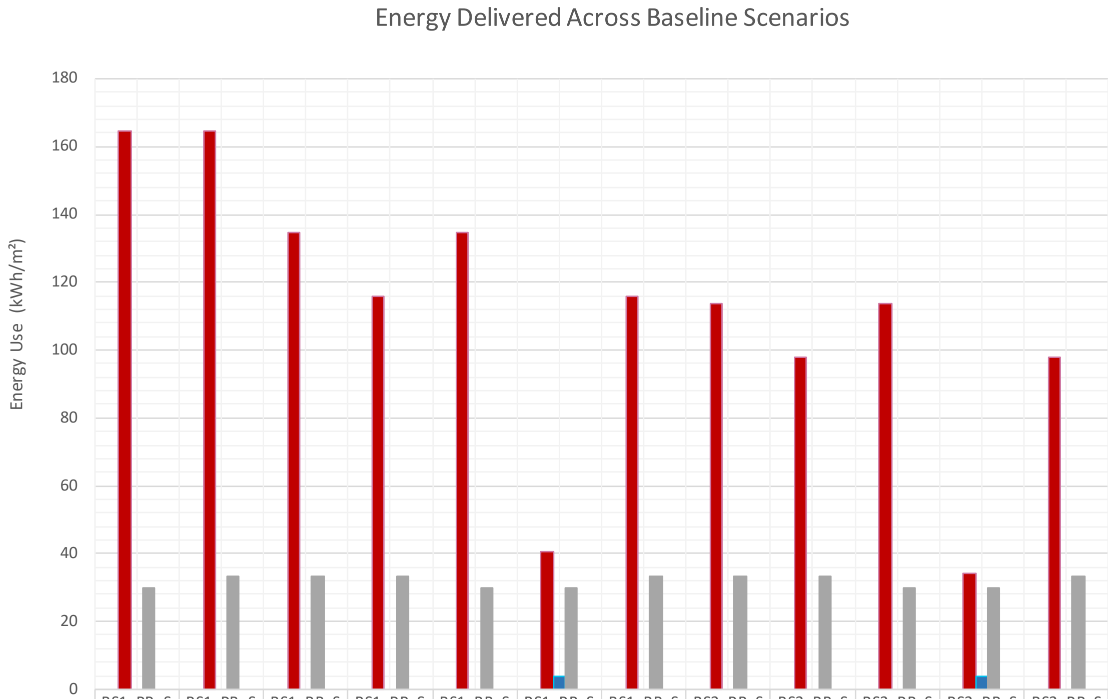


Figure 3.92 Comparison of Energy Need (heating, cooling, and DHW) results for all baseline scenarios

The graph shows how the energy need changes between different scenarios as insulation and ventilation measures are introduced. The first three bars represent cases without mechanical ventilation, where air exchange occurs naturally through infiltration and exfiltration. The next bar shows the increase in heating demand when mechanical ventilation without heat recovery is added, designed to achieve better indoor climate; the same level of indoor air quality is achieved, but the supply air has to be fully heated, which increases the total heating energy use. The last bar represents scenario where the heat supply system is changed so that active cooling is also available; here the total energy includes both heating and the additional cooling energy needed to prevent excessively high indoor temperatures in summer.

Energy Delivered

Figure 3.93 presents delivered energy use for space heating, domestic hot water (DHW) and cooling for the same baseline scenarios as in Figure 3.92. While Figure 3.92 showed the thermal energy need at building level, this figure presents the energy delivered to the building, i.e. the energy use after accounting for the efficiencies of the heat supply systems (e.g. boilers, district heating substation, electric heating) and the emission factors associated with the different systems. As a consequence, scenarios with less efficient heat sources require more delivered energy per square metre, whereas more efficient systems can cover the same thermal demand with lower delivered energy use. DHW remains almost constant at about 30–33 kWh/m² in all cases, heating still dominates the total delivered energy, and cooling energy appears only in the scenarios where active cooling is available.



	BS1_PB_SC1_ES1_electricity	BS1_PB_SC1_ES1_gas	BS1_RB_SC1_ES1_vent0.35	BS1_RB_SC2_ES1_vent0.35	BS1_RB_SC1_ES2_vent0.35	BS1_RB_SC2_ES2_vent0.35	BS1_RB_SC3_ES3_vent0.35	BS2_RB_SC1_ES1_vent0.35	BS2_RB_SC2_ES1_vent0.35	BS2_RB_SC1_ES2_vent0.35	BS2_RB_SC2_ES2_vent0.35	BS2_RB_SC3_ES3_vent0.35
Heating	165	165	135	116	135	40	116	114	98	114	34	98
Cooling	0	0	0	0	0	4	0	0	0	0	4	0
DHW	30	33	33	33	30	30	33	33	33	30	30	33

Figure 3.93 Comparison of Energy Delivered (heating, cooling, and DHW) results for all baseline scenarios. It should be noted that Energy Delivered for heating and DHW refers to thermal energy, while that for cooling refers to electrical energy

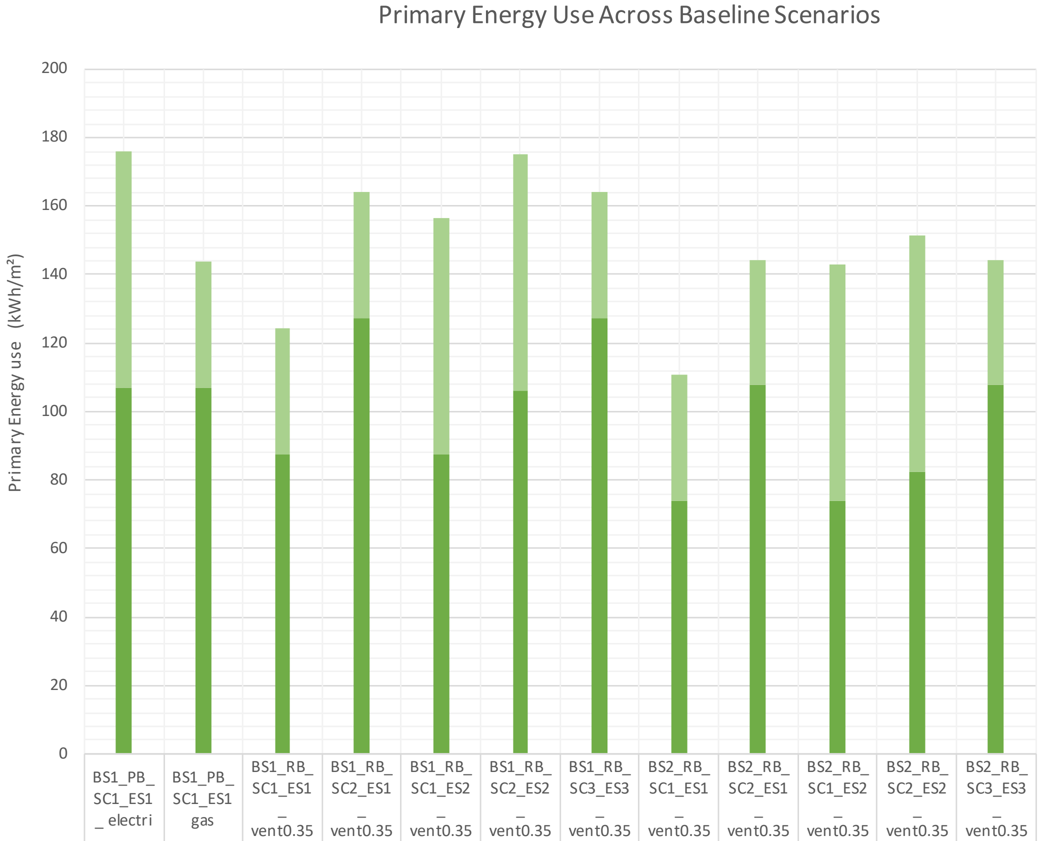
While insulation measures provide a real reduction in thermal energy need at building level, the change in delivered energy can look quite different and strongly depends on the chosen reference situation. In the delivered-energy graph, an apparent energy saving may be achieved simply by replacing inefficient heat supply systems in the pre-renovation condition with more efficient ones, even if the building's fabric and ventilation strategy remain unchanged. For example, over time a shift from traditional stove heating to a gas boiler with radiators, or an even larger change to a heat-pump-based system, substantially reduces the delivered energy compared to the original situation. In such cases, the reduction in delivered energy reflects the improved system efficiencies rather than an actual decrease in the building's underlying energy need. This graph highlights how total energy delivered decreases after renovation.

The graph includes only the energy used for space heating, heating of the ventilation supply air and, where applicable, space cooling. It does not show the auxiliary electricity required to operate the different systems (e.g. fans, circulation pumps). For heat pumps, the electricity needed to run the unit is implicitly accounted for through the assumed COP value.

Primary Energy Use

The comparison of primary energy use is based on a set of pre- and post-renovation energy supply scenarios. Primary energy does not only depend on the building's thermal demand, but also on the type of energy carrier and its associated primary energy factor; therefore, scenarios with similar delivered energy can result in markedly different primary energy use. The magnitude of the apparent "saving" or "reduction" in primary energy is therefore highly sensitive to both the initial situation and the chosen renovation pathway, as illustrated by the pre-renovation energy supply schemes in D5.4 Section 5.4.4 (Figure 37, scenarios ES1_PB–ES2_PB) and the corresponding renovation schemes in Section 5.5.4 (Figure 40, scenarios ES1_RB–ES4_RB).

Figure 3.94 presents a comparison of primary energy use for space heating, cooling and domestic hot water (DHW) for all baseline scenarios. The percentage values indicate the reduction in primary energy compared to the related pre-renovation scenario. The resulting primary energy saving strongly depends on the initial energy supply situation and on the heat carrier used. Since primary energy is obtained by multiplying the delivered energy by carrier-specific primary energy factors, a reduction in thermal energy use does not necessarily translate into a proportional reduction in primary energy. In some renovation paths, the energy need for heating is reduced but the heat supply is shifted from a carrier with a low primary energy factor (e.g. biomass 0.65 or efficient district heating 0.65) to one with a higher factor (e.g. electricity 2.3). In such cases, the apparent energy saving at the level of delivered heat may partly disappear when assessed in terms of primary energy.

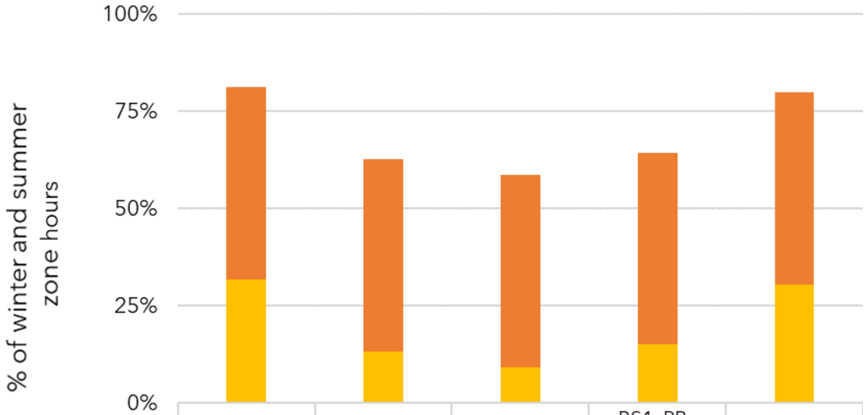


	BS1_PB_SC1_ES1_electri	BS1_PB_SC1_ES1 gas	BS1_RB_SC1_ES1_vent0.35	BS1_RB_SC2_ES1_vent0.35	BS1_RB_SC1_ES2_vent0.35	BS1_RB_SC2_ES2_vent0.35	BS1_RB_SC3_ES3_vent0.35	BS2_RB_SC1_ES1_vent0.35	BS2_RB_SC2_ES1_vent0.35	BS2_RB_SC1_ES2_vent0.35	BS2_RB_SC2_ES2_vent0.35	BS2_RB_SC3_ES3_vent0.35
DHW	69	37	37	37	69	69	37	37	37	69	69	37
Heating and cooling	107	107	88	127	88	106	127	74	108	74	83	108
Energy saving %		18%	29%	7%	11%	0%	7%	37%	18%	19%	14%	18%

Figure 3.94 Comparison of Primary Energy (heating/cooling and DHW) results for all baseline scenarios. The percentage indicates the reduction in primary energy compared to the related pre-renovation scenario.

When the primary energy graph is compared with the delivered energy graph, it becomes evident that in some scenarios the delivered energy (kWh/m²) clearly decreases, whereas the corresponding primary energy use does not show the same reduction and may even remain almost unchanged. This happens because the primary energy result is strongly influenced by changes in the heat carrier and its primary energy factor, so a saving in delivered heat does not automatically translate into a saving in primary energy, especially if inappropriate choices are made regarding the heat supply. Within the set of options considered here, upgrading the heating system towards an efficient district heating connection is one of the few renovation pathways that can provide consistent savings, benefitting both from improved system efficiency and from favourable primary energy factors.

Thermal Comfort



	BS1_PB	BS1_RB	BS2_RB	BS1_PB_ vent 0.35	BS2_RB cool
Winter period - h	6480	6480	6480	6458	6480
Summer period - h	4174	1740	1199	1970	3980
Winter period %	49%	49%	49%	49%	49%
Summer period %	32%	13%	9%	15%	30%

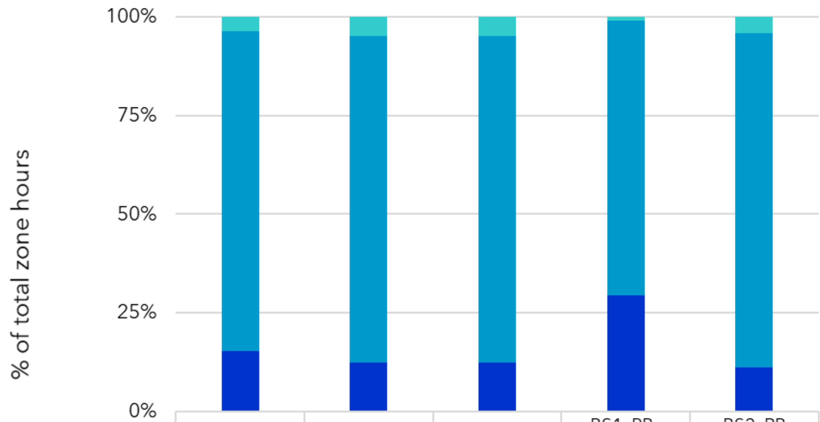
Figure 3.95 Comparison of Thermal Comfort (number of hours and % of time for winter and summer period inside CATII) results for all baseline scenarios

In addition to the energy performance, the indoor thermal environment was evaluated in accordance with EN 16798-1 using the adaptive thermal comfort categories I–III. Figure 3.95 presents the share of zone hours during the winter and summer periods that fall inside Category II for the pre-renovation case BS1_PB, the renovation scenarios BS1_RB and BS2_RB, the variant with increased ventilation BS1_PB_vent0.35, and the renovation case with active cooling BS2_RB_cool. The y-axis shows the percentage of all winter and summer zone hours.

For all scenarios, approximately 49 % of the total winter zone hours are within Category II, indicating that the heating system capacity is sufficient to maintain acceptable indoor temperatures in winter, regardless of envelope renovation or changes in the ventilation and cooling strategy. The behaviour in summer is more sensitive to the renovation measures. In the pre-renovation case BS1_PB, about 32 % of the summer hours are in Category II. After stepwise envelope renovation without cooling (BS1_RB and BS2_RB), the share of Category II hours decreases to 13 % and 9 %, respectively, reflecting an increased tendency towards higher operative temperatures and hence a greater risk of overheating in the better-insulated variants. The increased-ventilation case BS1_PB_vent0.35 shows a modest change compared with BS1_PB, with around 15 % of the summer hours in Category II, indicating that higher airflow slightly alleviates overheating but also shifts part of the time towards cooler (Category I) conditions. In contrast, the scenario BS2_RB_cool, where active cooling is introduced in the renovated envelope, restores the share of Category II hours to about 30 %, demonstrating that cooling is effective in recovering summer thermal comfort in the highly insulated configuration.

It should be noted that the simulations do not account for window airing, and therefore short periods with locally reduced indoor temperatures due to manual window opening are not reflected in the results. Overall, the analysed measures do not compromise winter thermal comfort and show that envelope improvements alone tend to increase the risk of summer overheating, whereas increased ventilation and especially active cooling can partially or largely compensate for this effect.

Relative Humidity



	BS1_PB	BS1_RB	BS2_RB	BS1_PB_ vent 0.35	BS2_RB cool
Above 70% - h	987	1297	1280	615	1093
Between 30% & 70% - h	21298	21704	21729	42615	22282
Below 30% - h	4001	3285	3277	18104	2911
Above 70%	4%	5%	5%	1%	4%
Between 30% & 70%	81%	83%	83%	69%	85%
Below 30%	15%	12%	12%	30%	11%

Figure 3.96 Comparison of Relative Humidity results for all baseline scenarios. The graph shows the number of hours and % of time inside the optimal range for RH (30-70%), below 30% of RH and above 70% of RH

Figure 3.96 shows the distribution of indoor relative humidity (RH) for the BS1 wooden-building scenarios. Results are expressed as the percentage of total zone hours with RH below 30 %, between 30 % and 70 %, and above 70 %, where 30–70 % is taken as the desirable comfort interval. The figure includes the pre-renovation case BS1_PB, the renovation scenarios BS1_RB and BS2_RB, the variant with increased ventilation BS1_PB_vent0.35, and the renovated case with active cooling BS2_RB_cool.

In the reference case BS1_PB, about 81 % of all zone hours lie within the 30–70 % range. Approximately 4 % of the hours exceed 70 % RH, while around 15 % are drier than 30 % RH. This indicates that indoor air is mostly within the recommended comfort band, with occasional periods of both elevated and low humidity. In the renovation scenarios BS1_RB and BS2_RB, the share of hours in the comfort range increases slightly to 83–83 %, while the fraction of very dry conditions drops to about 12 % and the share of hours above 70 % RH remains small (around 5 %). Thus, envelope renovation alone does not introduce additional moisture problems and even marginally improves the distribution.

A different pattern appears in the increased-ventilation case BS1_PB_vent0.35. Here, the proportion of hours with high humidity (RH > 70 %) is reduced to about 1 %, confirming that higher air exchange effectively removes moisture peaks. At the same time, the share of hours within the comfort interval decreases to 69 %, and the fraction of very dry conditions (RH < 30 %) rises to about 30 %, reflecting the pronounced drying effect of the higher ventilation rate. In the BS2_RB_cool scenario, relative humidity remains favourable: around 85 % of the hours are within 30–70 %, roughly 4 % above 70 %, and about 11 % below 30 %, comparable or slightly better than in the reference case.

Overall, the simulations show that relative humidity remains predominantly within acceptable limits in all BS1 scenarios. Increased ventilation further reduces the risk of high humidity, but it also substantially increases the number of hours with low RH, which may be relevant when considering occupant comfort and the potential need for local humidification or other mitigation measures during the heating season.

CO_2 Concentration

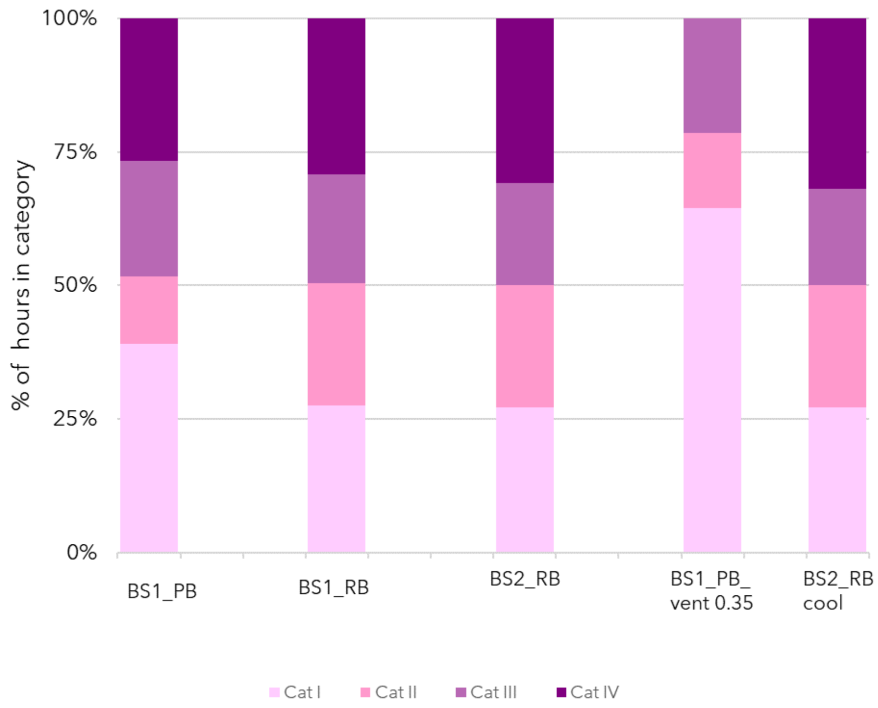


Figure 3.97 Distribution of CO_2 concentration levels for the BS1 scenarios

Figure 3.97 shows the distribution of indoor CO_2 concentration levels for the BS1 wooden-building scenarios. The results are expressed as the percentage of total zone hours in four CO_2 categories (Cat I–IV), where Category I represents the best air quality (lowest CO_2 levels) and Category IV the poorest. The figure includes the pre-renovation case BS1_PB, the renovation scenarios BS1_RB and BS2_RB, the variant with increased ventilation BS1_PB_vent0.35, and the renovated case with active cooling BS2_RB_cool. In the reference case BS1_PB, indoor air quality is clearly sub-optimal: only a minority of the hours fall into Categories I–II, while more than half of the time is spent in Categories III–IV. This indicates that elevated CO_2 levels occur frequently in the existing configuration and that the baseline ventilation is insufficient to provide consistently good air quality. In the renovation scenarios BS1_RB and BS2_RB, where the envelope is improved but the ventilation strategy is unchanged, the distribution remains dominated by Categories III and IV and the share of hours in Category I even decreases slightly compared with BS1_PB. This suggests that the reduced infiltration resulting from better airtightness is not compensated by increased intentional ventilation, so envelope renovation alone does not improve – and may slightly worsen – CO_2-based air quality. A different picture is obtained for the variant BS1_PB_vent0.35. Here, the majority of hours shift into Category I, with most of the remaining time in Category II, while Categories III and IV are strongly reduced. This shows that increasing the mechanical ventilation rate has a pronounced positive impact on indoor air quality for the pre-renovation envelope. In the BS2_RB_cool scenario, the distribution of CO_2 categories is similar to the other renovated cases without enhanced ventilation, confirming that adding active cooling does not in itself affect CO_2 concentrations; the key factor for air quality remains the ventilation rate rather than the thermal system.

As for the other CO_2 analyses, it should be noted that the simulations do not include any window opening for airing, because no reliable window-opening profile was available. The results therefore represent a conservative, worst-case estimate compared with real operation, where occupants are likely to open windows at least occasionally. Moreover, the renovation scenarios involve reduced air leakage due to improved airtightness, which underlines that, when tightening the envelope, sufficient intentional ventilation must be provided to maintain adequate indoor air quality. Overall, the table and figure demonstrate that increasing the ventilation rate substantially improves indoor air quality by shifting a growing share of hours into Categories I and II and completely removing Category IV conditions.

3.4.3. Brick apartment building

Stalinist style apartment buildings constructed in 1940-1955 represent a variety of buildings both small and large, wooden and brick. In this project, Stalinist style buildings made of brick were selected. In Estonia, this type of apartment buildings were built in place of those destroyed in WWII and constructed mainly to accommodate workers who immigrated from Soviet Russia. Behind the highly decorated facades were often apartments with simple living conditions and little decoration.

Figure 3.98 Aerial view of the brick building surroundings and facade of the building.

Results for Pre-renovation and Renovation baseline scenario

According to D5.4, the Pre-renovation baseline scenarios defined for the Estonian archetypes are shown in the scheme below.

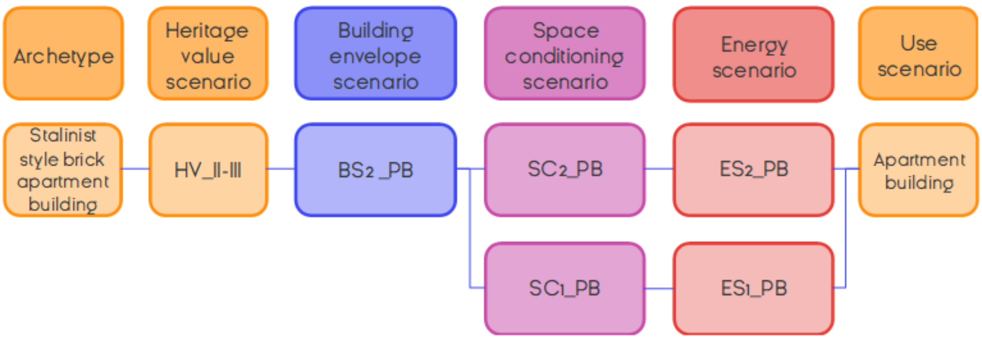


Figure 3.99 Overview of the Pre-renovation baseline scenarios for the Estonian archetypes

Similarly, based on D5.4, the Renovation baseline scenarios defined for the Estonian archetypes are shown in the scheme below.

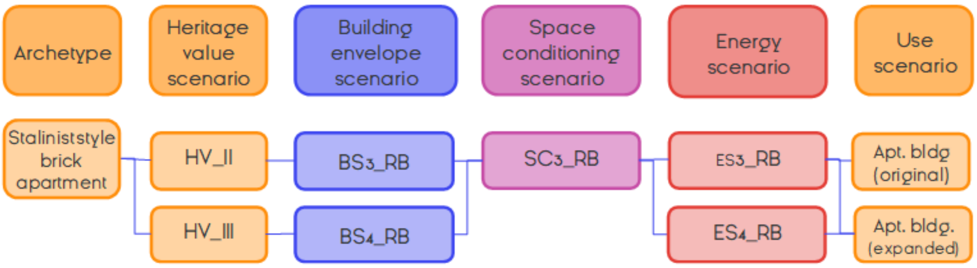


Figure 3.100 Overview of the Renovation baseline scenarios for the Estonian archetypes

The operational information has been implemented into the model to reflect the standard use of the building, as described in section 3.4.1. As far as the generation system is concerned, there are different systems considered to produce domestic hot water and heating. In the following tables are reported the U value for each building component, the air leakage rate qE50 and the overall efficiencies of the technical systems (ηsys) for the archetype analysed.

Pre-Renovation		Renovation	
U-Value [W/m²K]			
Compo-nent	Pre-reno, BS2_PB	Reno, BS3_RB	Reno, BS4_RB
Exterior wall	1.5	1.5	0.45[1]
Internal wall	1	1	1
Ground floor	1	0.4	0.18
Interior floor	0.9	0.9	0.9
Attic floor	0.75	0.25	0.75
Roof			0.2
Windows	2.9	1.5	1.5
Air Leakage Rate [m³/h·m²]			
q_{E50}	10	4	4

Overall efficiency of technical systems						
	Pre-Renovation			Renovation		
	ES1_PB	ES1_PB	ES2_PB	ES3_RB	ES4_RB	ES4_RB
$\eta_{sys, heatsource}$	0.75	0.75	0.9	0.9	0.9	0.9
$\eta_{sys, heat-system}$			0.97	0.97	0.97	0.97
$\eta_{sys, DHW}$	1	0.9	0.9	0.9	0.9	1
$\eta_{sys, cooling}$	x			x	x	x
Ventilation [l/s·m²]						

$q_{vent, air flow}$	*nat*[2]	0.35[3]
$\eta_{sys, ventilation heat recovery}$	x	x
[1] *weighted average* [2] *nat – natural (air leakages + window airing converted into an equivalent ventilation airflow rate of 0.05 l/s·m²)* [3] *airflow rate l/s per square meter of heated area*		

Table 3.24 Main information on U-value, Air Leakage Rate and Air change Rate for infiltration and overall efficiency of the technical systems adopted in the different Pre-renovation and Renovation baseline scenarios for the Wooden apartment Archetype

Following the estimation of the main output related to energy, comfort and IAQ aspects for each baseline scenario are presented.

The indoor climate graphs represent the conditions corresponding to the different insulation scenarios and changes in ventilation in the pre-renovation case. They do not coincide with the delivered and primary energy graphs, since the latter also reflect changes in the heat source and heating system.

Energy Need

Energy demand for heating, domestic hot water (DHW) and cooling across the baseline scenarios is presented in Figure 3.101. All values represent energy need at building level; system efficiencies and heat supply / distribution losses are not taken into account. Each stacked bar represents one scenario and shows the contribution of space heating (red), DHW (grey) and, where relevant, space cooling (blue) in kWh/m² of floor area.

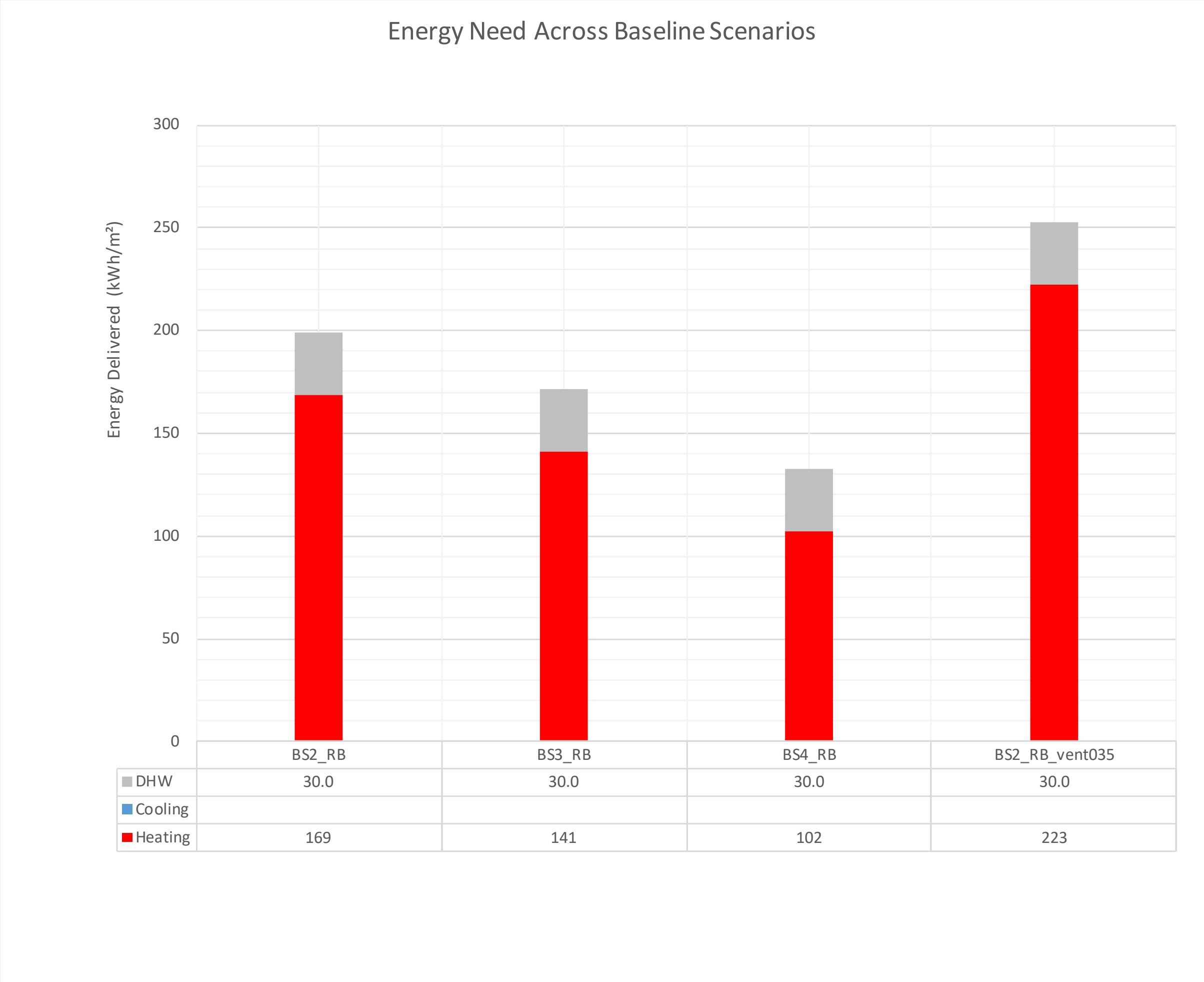


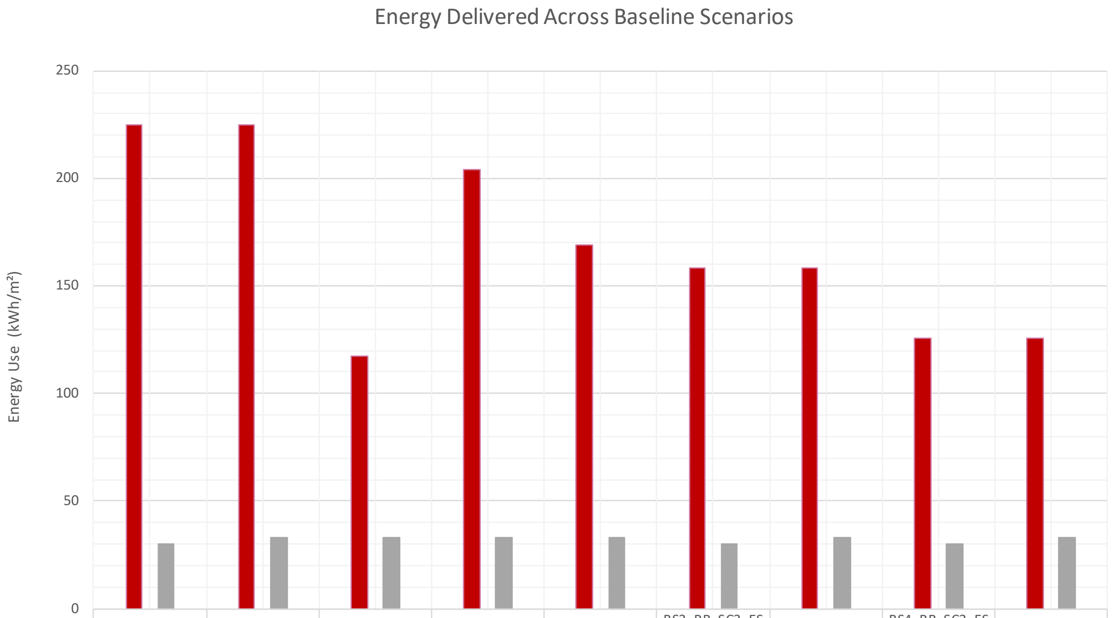
Figure 3.101 Comparison of Energy Need (heating, cooling, and DHW) results for all baseline scenarios

The results are presented for three renovation baseline envelope levels (BS2_RB, BS3_RB and BS4_RB) and for one variant with increased ventilation airflow (BS2_RB_vent035). The stacked columns indicate the contribution of space heating and DHW in kWh/m²·year. DHW demand is kept constant at 30 kWh/m²·year in all scenarios, while space heating clearly dominates the total energy need.

Moving from BS2_RB to BS4_RB, the calculated heating need decreases from 169 to 102 kWh/m²·year, reflecting the effect of improved insulation and airtightness of the building envelope. The variant BS2_RB_vent035, where a higher ventilation airflow rate of 0.35 l/s·m² is applied, shows a substantially higher heating need of 223 kWh/m²·year compared with the corresponding BS2_RB case. This highlights the sensitivity of the total energy need to ventilation losses in a cold climate, and the importance of combining increased airflow with measures such as heat recovery if higher indoor air quality is to be achieved without a large penalty in heating demand.

Energy Delivered

Figure 3.105 shows the delivered energy use for space heating and domestic hot water (DHW) for the Estonian brick apartment building. In contrast to the energy-need results, the values here include the efficiencies of the heat source and the distribution/emission system, so the columns represent the energy that must be supplied by the energy carrier (electricity, gas or district heating).



	BS2_PB_SC1_ES 1 electricity	BS2_PB_SC1_ES 1_ gas	BS3_PB_SC2_PB _ES2_ PB	BS3_RB_SC3_ES 3 _vent0.35	BS4_RB_SC3_ES 3_ vent0.35	BS3_RB_SC3_ES 4_ vent0.35 electricity	BS3_RB_SC3_ES 4_ vent0.35 gas	BS4_RB_SC3_ES 4_ vent0.35 electricity	BS4_RB_SC3_ES 4_ vent0.35 gas
Heating	225	225	117	204	169	158	158	126	126
Cooling	0	0	0	0	0				
DHW	30	33	33	33	33	30	33	30	33

Figure 3.102 Comparison of Energy Delivered (heating, cooling, and DHW) results for all baseline scenarios. It should be noted that Energy Delivered for heating and DHW refers to thermal energy, while that for cooling refers to electrical energy

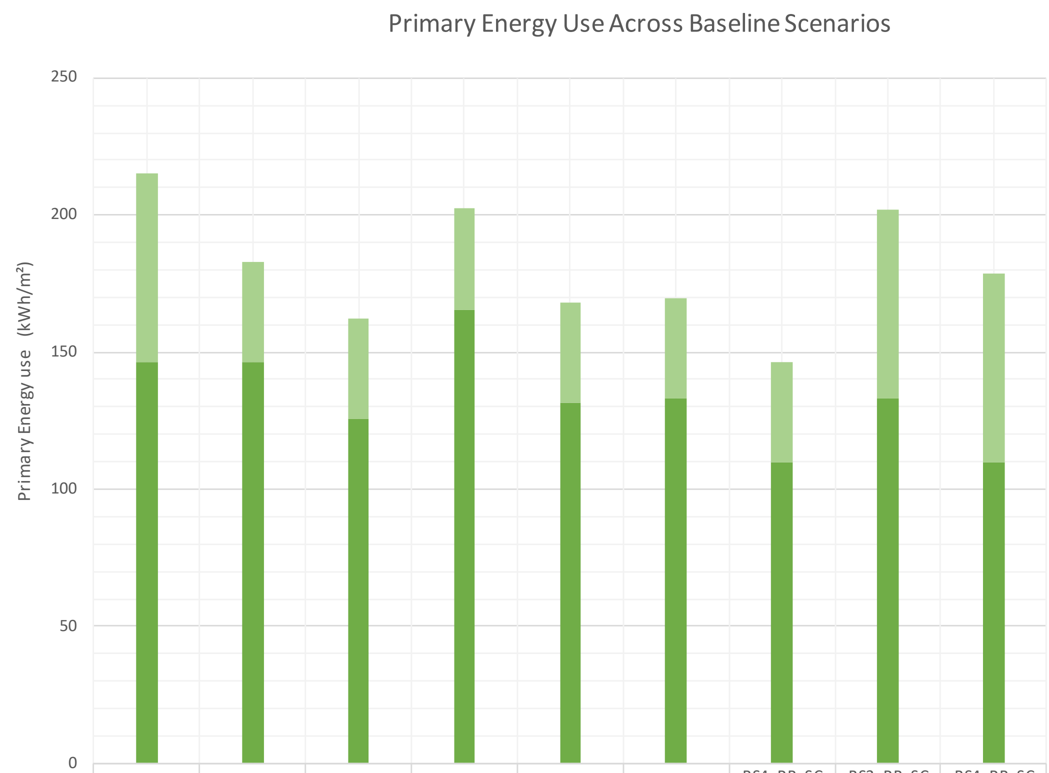
The first two columns represent pre-renovation cases with stove heating, where space heating is provided by masonry stoves and DHW is produced by decentral gas and electric water heaters, respectively. The third column corresponds to a pre-renovation case with radiator heating supplied by district heating, while DHW is still generated by gas. The next group of columns shows renovation scenarios in which the building envelope has been improved and both space heating and DHW are supplied by apartment-based gas boilers. The following columns represent variants where space heating is supplied by district heating, whereas DHW is produced by decentral gas or electric boilers. In the last group, the renovation level of the building envelope is further improved, while the combinations of heating and DHW production follow the same patterns as in the preceding group.

Across the figure, DHW remains nearly constant at about 30–33 kWh/m²·year, whereas delivered energy for space heating varies substantially. The shift from pre-renovation to renovation scenarios leads to a marked reduction in delivered heating energy, driven mainly by better insulation and airtightness, while differences between the various energy-supply options reflect the assumed efficiencies of the heat sources and distribution systems.

Primary Energy Use

For the brick case-study building, primary energy use is evaluated for a set of pre- and post-renovation energy supply scenarios. As for the wooden buildings, primary energy does not only depend on the building's thermal demand and on the delivered energy, but also on the type of heat carrier and its associated primary energy factor. Consequently, scenarios with comparable delivered energy may lead to noticeably different primary energy use once the carrier-specific factors are applied.

Figure 3.103 presents the primary energy use for space heating and domestic hot water (DHW) for all baseline scenarios. The stacked bars show the separate contributions from DHW and from heating, while the percentage below each column indicates the reduction in primary energy compared to the corresponding pre-renovation case. The first two scenarios represent pre-renovation situations with stove heating and decentral DHW production, either with electricity or gas. The third column illustrates a pre-renovation configuration with radiator heating supplied by district heating and gas-fired DHW. The remaining columns show renovation scenarios with improved envelope performance, combined with different energy supply options: apartment-based gas boilers for both heating and DHW, district heating for space heating with gas-fired DHW, and district heating for space heating with electrically heated DHW.



	BS2_PB_SC 1_ES1 electricity	BS2_PB_SC 1_ES1_ gas	BS3_PB_SC 2_PB_ES2_ PB	BS3_RB_SC 3_ES3_vent 0.35	BS4_RB_SC 3_ES3_ vent0.35	BS3_RB_SC 3_ES4_vent 0.35 gas	BS4_RB_SC 3_ES4_ vent0.35 gas	BS3_RB_SC 3_ES4_vent 0.35 electricity	BS4_RB_SC 3_ES4_ vent0.35 electricity
DHW	69	37	37	37	37	37	37	69	69
Heating and cooling	146	146	126	166	132	133	110	133	110
Energy saving %		15%	25%	6%	22%	21%	32%	6%	17%

Figure 3.103 Comparison of Primary Energy (heating/cooling and DHW) results for all baseline scenarios. The percentage indicates the reduction in primary energy compared to the related pre-renovation scenario.

The results confirm that the magnitude of the apparent “saving” in primary energy is strongly influenced by both the initial configuration and the selected renovation pathway. Renovation of the building envelope clearly reduces the primary energy use for heating; however, the total primary energy performance also depends on whether DHW is produced with gas or with electricity and on whether space heating is supplied by district heating or by apartment-based gas boilers. For example, scenarios with electric DHW show a noticeably higher primary energy contribution from DHW than otherwise comparable gas-based solutions, despite similar delivered energy. When these primary energy results are compared with the delivered-energy graphs, it becomes evident that a reduction in delivered heat does not automatically translate into an equally large reduction in primary energy: the choice of heat carrier and its primary energy factor can partly offset or, in favourable cases (e.g. efficient district heating 0.65 with gas-fired DHW 1.1), enhance the savings achieved through envelope renovation.

Thermal Comfort

	BS2_PB	BS3_RB	BS4_RB	BS2_PB_ vent0.35
Winter period - h	12960	12960	12960	12960
Summer period - h	5331	4905	41	7445
Winter period %	49%	49%	49%	49%
Summer period %	20%	19%	0%	28%

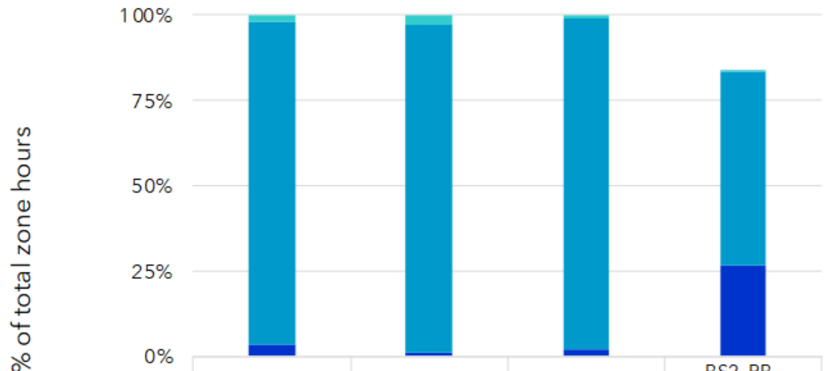
Figure 3.104 Comparison of Thermal Comfort (number of hours and % of time for winter and summer period inside CATII) results for all baseline scenarios

For the BS2 variants, indoor thermal conditions were evaluated according to EN 16798-1 using adaptive thermal comfort Category II as reference. Figure 3.101shows the share of winter and summer zone hours that fall within Category II for the pre-renovation case BS2_PB, the renovation scenarios BS3_RB and BS4_RB, and the variant with increased ventilation BS2_PB_vent0.35. The y-axis indicates the percentage of all winter and summer zone hours.

In all scenarios, around 49 % of the winter hours are within Category II, indicating that the heating system capacity is sufficient to maintain acceptable indoor temperatures during the heating season, regardless of envelope improvements or changes in ventilation. In the pre-renovation case BS2_PB, about 20 % of the summer hours meet Category II. With the stepwise envelope renovation in BS3_RB and BS4_RB, the fraction of summer hours in Category II decreases to 19 % and effectively 0 %, respectively, reflecting an increased tendency towards overheating in the better-insulated variants when no active cooling is provided.

In contrast, the variant BS2_PB_vent0.35 shows an improvement in summer comfort compared to BS2_PB: the share of Category II hours rises from 20 % to 28 %, while winter conditions remain unchanged at 49 %. This indicates that a higher ventilation rate can partially mitigate summer overheating in the existing envelope configuration. It should be noted that window airing is not considered in the simulations; therefore, short-term local reductions in indoor temperature due to manual window opening are not captured by the results.

Relative Humidity



	BS2_PB	BS3_RB	BS4_RB	BS2_PB_ vent0.35
Above 70% - h	982	1324	592	19
Between 30% & 70% - h	49890	42146	50973	29891
Below 30% - h	1700	340	995	13900
Above 70%	2%	3%	1%	0%
Between 30% & 70%	95%	96%	97%	57%
Below 30%	3%	1%	2%	26%

Figure 3.105 Comparison of Relative Humidity results for all baseline scenarios. The graph shows the number of hours and % of time inside the optimal range for RH (30-70%), below 30% of RH and above 70% of RH

Figure 3.105 shows the distribution of indoor relative humidity (RH) for the BS2 brick-building scenarios. Results are expressed as the percentage of total zone hours with RH below 30 %, between 30 % and 70 %, and above 70 %, where 30–70 % is taken as the desirable comfort range. The figure includes the pre-renovation case BS2_PB, the renovation scenarios BS3_RB and BS4_RB, and the variant with increased ventilation BS2_PB_vent0.35. In the pre-renovation case BS2_PB, indoor humidity is already very stable: about 95 % of all zone hours lie within the 30–70 % interval. Only 2 % of the hours exceed 70 % RH, and around 3 % are below 30 %, so both excessively humid and very dry conditions occur only occasionally. After envelope renovation (BS3_RB and BS4_RB), the situation improves slightly: 96–97 % of the hours remain within the comfort range, while the shares of hours above 70 % RH and below 30 % RH are reduced to 1–3 %. This indicates that the renovated envelopes do not introduce additional moisture problems.

In contrast, the variant BS2_PB_vent0.35, where the ventilation rate is increased without changing the envelope, the fraction of hours in the comfort band drops to about 57 %, while dry conditions (RH < 30 %) rise to roughly one quarter of the total time. As observed for the BS1 cases, this illustrates the drying effect of higher air exchange: moisture peaks are effectively removed, but the indoor air becomes considerably drier over large parts of the year.

The simulations may not fully capture additional internal moisture loads identified in measurements; nevertheless, the results show that increased ventilation is beneficial in situations with elevated moisture gains, as it limits high RH peaks that could become critical during the cold season. Overall, all BS2 scenarios keep relative humidity predominantly within acceptable limits, but high ventilation rates clearly increase the number of hours with low RH, which should be considered when assessing occupant comfort.

CO_2 Concentration

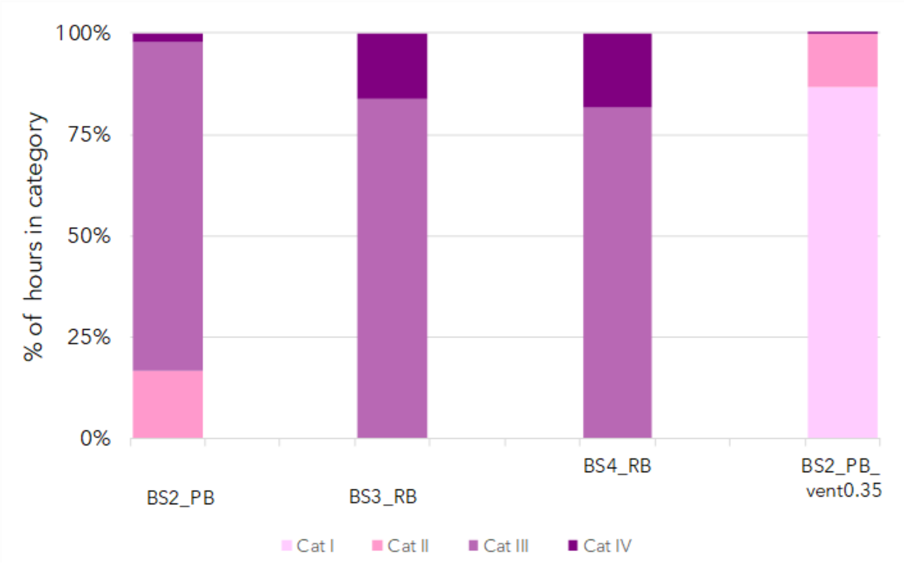


Figure 3.106 Distribution of CO_2 concentration levels for the BS1 scenarios

Figure 3.106 shows the distribution of indoor CO_2 concentration levels for the BS2 brick-building scenarios. Results are expressed as the share of total zone hours in four categories (Cat I–IV), where Category I represents the lowest CO_2 concentrations (best air quality) and Category IV the poorest air quality. In the pre-renovation case BS2_PB, indoor air quality is generally poor: only a small share of the hours falls into Category I, while almost all of the remaining time is spent in Categories III and IV. This means that elevated CO_2 levels occur during the vast majority of the occupied period, indicating insufficient ventilation in the existing configuration. In the renovation scenarios BS3_RB and BS4_RB, where the envelope is improved but the ventilation concept remains unchanged, the distribution is still dominated by Category III (and partly Category IV), with essentially no hours in Categories I–II. This confirms that envelope renovation alone does not resolve the air-quality issue for this archetype. Different picture emerges for the variant BS2_PB_vent0.35. Here, the majority of hours move into Category I, with the remainder in Category II, while Categories III and IV disappear completely. In this configuration, 100 % of the time is therefore spent in the two best air-quality categories, demonstrating that a higher, controlled ventilation rate can effectively eliminate periods with high CO_2 concentrations. As for the BS1 cases, it should be noted that the simulations do not include any window opening for airing, because no reliable window-opening profile was available. The results therefore represent a conservative, worst-case estimate compared with real operation, where occupants are likely to open windows at least occasionally. Moreover, the renovation scenarios involve reduced air leakage due to improved airtightness, which further underlines that, when tightening the envelope, sufficient intentional ventilation must be provided to maintain adequate indoor air quality.

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3.4.4. Lessons learnt

For the Estonian archetypes – the wooden and the brick apartment building – the simulations confirm that envelope renovation is the main lever for reducing heating demand. Additional insulation, tighter envelopes and better windows lead to a clear stepwise reduction in heating energy need. The results also show that higher ventilation rates without heat recovery can quickly erode these gains, especially in the cold Estonian climate, which underlines the need to couple increased airflow with efficient heat-recovery ventilation rather than simple extract systems.

When the performance is assessed in terms of delivered and primary energy, the influence of the heat supply systems becomes evident. Keeping the envelope constant but replacing traditional stoves with gas boilers or district heating already lowers delivered energy because of higher generation and distribution efficiencies. However, primary energy savings are strongly affected by the choice of energy carrier: switching from biomass or efficient district heating to electricity – particularly for DHW – can significantly limit, or partly offset, the gains achieved through envelope improvements. This means that, for these building types, deep reductions in primary energy require both a well-insulated envelope and careful selection of low-factor heat carriers.

Regarding indoor climate, pre-renovation conditions are acceptable but clearly not optimal in winter; improved envelopes help maintain the 21 °C setpoint with fewer hours at low operative temperatures. In summer, both archetypes are vulnerable to overheating, and increased insulation tends to sharpen this risk unless combined with higher ventilation rates and, where available, active cooling. Indoor air quality indicators point in the same direction: higher ventilation rates greatly improve CO_2 levels and reduce periods with high relative humidity, but also increase the share of very dry hours during the heating season. Overall, the Estonian case studies show that successful renovation of these heritage apartment buildings requires a balanced package combining envelope upgrades, efficient and appropriately selected heat-supply systems, and ventilation solutions that safeguard both energy performance and indoor environmental quality.

4. Conclusion

The results reveal a coherent set of patterns that illustrate how heritage buildings respond to renovation when viewed through the combined lens of energy performance and indoor environmental quality. Despite the considerable diversity in climate, construction traditions and building typologies, several fundamental insights emerge.

First, the simulations confirm that envelope renovation measures are universally effective. Improvements in insulation, airtightness, and window performance consistently lead to substantial reductions in energy use and markedly better winter comfort conditions. It underscores that even in historically protected contexts, measured and well-targeted envelope upgrades remain one of the most powerful tools for reducing heating demand and improving indoor temperature stability.

Second, the results highlight a critical trade-off: as buildings become more airtight, their reliance on deliberate ventilation strategies increases sharply. In most pre-renovation scenarios, infiltration provided a significant uncontrolled portion of fresh air supply. Once this unintentional airflow is reduced through renovation, CO_2 accumulation becomes evident, particularly in bedrooms and small-volume spaces. This trend is visible across all countries but is especially pronounced where mechanical ventilation is not part of the renovation baseline. The findings thus reinforce that ventilation cannot be treated as an optional complement to energy efficiency, it is a core requirement for safeguarding indoor air quality in renovated heritage homes.

Third, summer comfort emerges as a context-dependent concern, particularly in warmer or urban climates. While winter comfort improves robustly across the board, several renovated scenarios show increased sensitivity to overheating due to higher insulation levels, reduced natural air leakage, and heritage-related constraints on solar shading. This indicates that future renovation strategies must adopt a more holistic approach that balances winter energy savings with summer thermal resilience.

Finally, the behaviour of indoor humidity demonstrates the strong interdependence between ventilation, climate, and building materials. High relative humidity conditions decrease after renovation, reducing the risk of moisture-related damage—an essential consideration in heritage conservation.

The baseline renovation scenarios analysed reflect contemporary, widely adopted renovation approaches, which are often associated with a significant impact on heritage buildings. Although these scenarios serve as a relevant benchmark for assessing energy and IEQ performance, in some cases, these may be difficult to apply due to conservation constraints. This highlights the importance of developing and accessing more tailored, heritage-compatible renovation strategies, such as those that will be explored within HeriTACE project, aimed at achieving a better balance between energy performance improvements, indoor environmental quality, and the safeguarding of cultural heritage.

Taken together, these insights show that successful heritage renovation requires holistic approach, where energy performance, comfort, indoor air quality, and moisture control are addressed simultaneously and with sensitivity to local climatic and cultural conditions.

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