



FuturHist

# Supporting tools (re)developed and tested



# Project Overview



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# Executive Summary

This deliverable presents the development, adaptation and testing of the core support tools that will form the FuturHist digital toolkit for planning energy renovations of historic buildings. The work focused on integrating heritage significance, technical compatibility, energy performance, life cycle cost, environmental impact, indoor environmental quality and smart readiness within a common decision-support framework.

A principal result is the successful development and validation of a decision-tree methodology that uses building typology, heritage considerations and user-defined priorities to identify and rank suitable renovation measures.

The project also established practical methods for assessing heritage impacts and technical compatibility, enabling non-specialist users to identify appropriate interventions. In parallel, pyBuildingEnergy was selected and tested as the toolkit's energy assessment engine, providing sufficiently accurate results for early-stage decision-making while requiring limited input data. Archetype models were developed to support rapid evaluation of renovation scenarios across different historic building typologies.

Overall, the deliverable demonstrates that the individual assessment methods and tools can operate together within a coherent decision-support workflow. The results are highly relevant to achieving the FuturHist project objectives because they transform the project's conceptual framework into practical tools that support balanced renovation decisions, combining energy efficiency and decarbonisation goals with the preservation of cultural heritage. The work provides an essential foundation for the final integration and deployment of the FuturHist toolkit.

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# Abbreviations and definitions

|                                          |                                                                                                                                                                                                                                               |
|------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>AAU</b>                               | Aalborg University, Denmark (FuturHist partner)                                                                                                                                                                                               |
| <b>Adaptation</b>                        | Other typologies (materials, geometry) in the same/similar context (climate, legislation).                                                                                                                                                    |
| <b>Archetype</b>                         | Theoretically defined buildings based on the typical or average census values.                                                                                                                                                                |
| <b>AVRA</b>                              | Agencia de Vivienda y Rehabilitación de Andalucía, Spain (FuturHist partner)                                                                                                                                                                  |
| <b>Baseline scenario</b>                 | The existing scenario before building retrofit.                                                                                                                                                                                               |
| <b>Be18</b>                              | Be18 is a calculation program that is used to document that a building complies with the Danish Building Regulations' energy provisions and to calculate energy needs and energy consumption in new construction.                             |
| <b>Building typology</b>                 | A set of buildings with common properties (e.g. age of construction, geometry, thermo-physical properties, and energy performance) (Institut Wohnen und Umwelt GmbH, 2012).                                                                   |
| <b>D</b>                                 | Deliverable.                                                                                                                                                                                                                                  |
| <b>Drupal</b>                            | Content Management System used as a platform for FuturHist toolkit.                                                                                                                                                                           |
| <b>Demo/demonstrator (building/case)</b> | A real building belonging to a typology which is used to demonstrate retrofitting solutions (also referred to as “DC”)                                                                                                                        |
| <b>DHW</b>                               | Domestic hot water, i.e. heating water for domestic or commercial purposes other than space heating and process requirements.                                                                                                                 |
| <b>Dimension</b>                         | The FuturHist methodology establishes a holistic assessment across six critical dimensions: Energy Performance, Heritage Significance, Life Cycle Assessment (LCA), Technical Compatibility, Financial Aspects (LCC), and User Aspects (IEQ). |
| <b>Energy calculator</b>                 | The core analytical function within the FuturHist Toolkit, responsible for estimating reduction in energy need for heating and cooling. It                                                                                                    |

generates paired scenarios: ex-ante (baseline) and ex-post (after proposed solutions).

|                                  |                                                                                                                                                                                                                                                                                                                          |
|----------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Environmental values</b>      | The dimension of the FuturHist toolkit focusing on balancing energy performance improvement with resource efficiency, aiming to avoid excessive use of resources on energy-saving solutions. Key concerns addressed include operational and embodied carbon, natural resource use, circularity, and biodiversity impact. |
| <b>EPW</b>                       | EnergyPlus Weather File (EPW) Format. The EPW weather data format was originally developed for use with two major simulation programs EnergyPlus and ESP-r and has since been adopted as a standard format by most other building simulation tools.                                                                      |
| <b>ERIK</b>                      | ERIK Arkitekter, Denmark (FuturHist partner).                                                                                                                                                                                                                                                                            |
| <b>EURAC</b>                     | Eurac Research, Italy (FuturHist partner).                                                                                                                                                                                                                                                                               |
| <b>EWB</b>                       | Edinburgh World Heritage, Scotland (FuturHist partner).                                                                                                                                                                                                                                                                  |
| <b>Heating Degree Days (HDD)</b> | A measure of how much (in degrees), and for how long (in days), outside air temperature was lower than a specific base temperature. They are used for calculations relating to the energy consumption required to heat buildings.                                                                                        |
| <b>Heritage significance</b>     | Combination of all the heritage values assigned to a building and its setting.                                                                                                                                                                                                                                           |
| <b>HVAC</b>                      | Heating, ventilation, and air conditioning.                                                                                                                                                                                                                                                                              |
| <b>IAQ</b>                       | Indoor air quality.                                                                                                                                                                                                                                                                                                      |
| <b>Ideal retrofit scenario</b>   | Retrofit scenario resulting in a minimum of 60 % reduction in non-renewable primary energy demand.                                                                                                                                                                                                                       |
| <b>IEQ</b>                       | Indoor environment quality.                                                                                                                                                                                                                                                                                              |
| <b>KPI</b>                       | Key performance indicator.                                                                                                                                                                                                                                                                                               |
| <b>KRAKOW</b>                    | The city of Krakow, Poland (FuturHist partner).                                                                                                                                                                                                                                                                          |
| <b>LCA</b>                       | Life cycle assessment for an intervention; a systematic method for evaluation the environmental impacts of a product, service or process. Calculated for a period of 50 years.                                                                                                                                           |

|                                             |                                                                                                                                                                                                                                                                                                                                                                            |
|---------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>LCC</b>                                  | Life cycle costing for an intervention; a method to calculate the economic impacts of a building or a product. Calculated for a period of 50 years.                                                                                                                                                                                                                        |
| <b>Material impact</b>                      | The extent to which the physical interventions introduced during a retrofit alter the historic building's existing fabric or its setting — and how this affects the heritage significance of the building and its settings.                                                                                                                                                |
| <b>Non-renewable primary energy demand</b>  | Amount of non-renewable primary energy needed to meet the energy demand associated with a typical use of the building, which includes energy used for heating, cooling, ventilation and domestic hot water (DHW).                                                                                                                                                          |
| <b>Non-renewable primary energy savings</b> | Difference in non-renewable primary energy demand before and after retrofit.                                                                                                                                                                                                                                                                                               |
| <b>Operational GHG emissions</b>            | Greenhouse gas emissions associated with the energy consumption of the technical building systems during the use and operation of the building.                                                                                                                                                                                                                            |
| <b>PBE</b>                                  | pyBuildingEnergy. An open-source Python library for building energy performance simulation developed by EURAC in the European projects Infinite (EU Horizon 2020, grant agreement No. 958397) and Moderate (Horizon Europe, grant agreement No. 101069834).                                                                                                                |
| <b>PK</b>                                   | Politechnika Krakowska, Poland (FuturHist partner)                                                                                                                                                                                                                                                                                                                         |
| <b>Real retrofit scenario</b>               | Retrofit scenario developed for actual implementation on a demonstrator building in the demonstration phase of the FuturHist project.                                                                                                                                                                                                                                      |
| <b>Replication</b>                          | Other buildings of the same typology.                                                                                                                                                                                                                                                                                                                                      |
| <b>Reversibility</b>                        | The potential of retrofit measures (materials, components, or alterations) to be removed, dismantled, or reversed without causing physical damage to the historic building's structure, finishes, or setting. Note: inappropriate retrofit interventions that would undermine the heritage significance of the building, even if they are reversible, should be discarded. |
| <b>SRI</b>                                  | Smart readiness indicator. A common European scheme introduced under the Energy Performance of Buildings Directive (EPBD) to evaluate the technological readiness of buildings to interact with                                                                                                                                                                            |

their occupants and connected energy grids, and to operate efficiently (European Parliament and Council, 2024).

**Spatial impact**

Spatial impact evaluates how the retrofit intervention alters the building's interior layout, volume, or external footprint, affecting its historic function, spatial experience, and relationship with its surroundings — and how this affects the heritage significance of the building and its settings.

**STRATH**

University of Strathclyde, Scotland (FuturHist partner).

**SVK**

Svenska Kyrkan, Sweden (FuturHist partner).

**T**

Task.

**Technical  
compatibility**

Technical compatibility is the degree to which a retrofit solution can be incorporated into an existing building while maintaining or improving the functional, structural, hygrothermal, durability, and operational performance of the building and its components.

**Transferability**

Similar typologies (materials, geometry) from another context (climate, legislation).

**UU**

Uppsala Universitet (FuturHist partner).

**U-value**

Thermal transmittance value, i.e., the rate of transfer of heat through a structure.

**Visual impact**

The extent of visual alterations to the building and its setting, both internally and externally, such as changes in color, style, or the addition of new visual elements that affect its character — and how this affects the heritage significance of the building and its settings.

**WHITE**

White Arkitekter (FuturHist partner).

**WP**

Work package.

# 1. Introduction

## 1.1. Overview of FuturHist

The FuturHist project is dedicated to addressing the challenge of energy retrofitting historic buildings while ensuring their long-term preservation and sustainability. Historic and traditional buildings constitute a significant portion of the European building stock and represent a key area of focus in the transition towards a low-carbon built environment. However, retrofitting these buildings is inherently complex due to their diverse construction techniques, material compositions, and heritage significance. Unlike modern structures, historic buildings require tailored solutions that balance energy efficiency improvements with the preservation of their heritage attributes.

To bridge this gap, FuturHist adopts a typology-based approach that allows for the identification and characterization of recurring building features in different regions. By defining common characteristics at the typology level, the project develops intervention strategies that can be standardized and replicated with minor adaptations, facilitating broader application across Europe. This approach enables a shift from a case-by-case assessment towards a more structured and scalable process, ensuring higher renovation rates and deeper interventions. The project builds upon established methodologies such as EN 16883 (European Committee for Standardization (CEN), 2017a), which provides guidelines for improving the energy performance of historic buildings. FuturHist advances these efforts by integrating performance indicators, decision support systems, and innovative technical solutions, ultimately streamlining the planning process for energy retrofits. The project also emphasizes the need for holistic assessment methods, ensuring that technical interventions are compatible with the built heritage while optimizing energy efficiency, indoor environmental quality, and cost-effectiveness.

Through the development of assessment categories and indicators, FuturHist provides a structured framework and a toolkit for evaluating retrofit measures and monitoring their impact. The project's outcomes will support practitioners (architects, engineers, owners etc.), policymakers (planners, heritage authorities etc.), and researchers in making informed decisions about energy retrofits in historic buildings, contributing to the broader goal of scaling up the sustainable transformation of existing buildings across Europe.

## 1.2. Objective and relation to previous FuturHist WPs

The objective of this deliverable is to present the tools selected for inclusion in the FuturHist toolkit and describe how, and to what extent they were (re)developed and tested to ensure their functionality within the toolkit.

The deliverable builds upon the foundations established in deliverable D1.2 ‘Building typology: analysis of the building stock and typologies definition’, D1.4 ‘Selection of tools: a review of guidelines and tools for energy retrofits in historic buildings’ (Hupkes, et al., 2025) , D1.6 ‘Assessment categories and KPIs: a multidimensional approach to performance assessment’ and D4.1 ‘Multidimensional decision-making methodology to identify an optimised solution for deep renovation of historic buildings’ (Sand, et al., 2026). D1.2 provides the typology framework that underpins the toolkit’s simplified, typology-based assessments. D1.4 identifies existing guidelines and tools that serve as inspiration and sources for adaptation. D1.6 defines the KPIs, indicators and decision criteria implemented throughout the assessment dimensions. D4.1 establishes the overall multidimensional decision-making methodology and identifies the approaches to be included in the toolkit. D4.2 translates these conceptual foundations into operational, tested decision-support tools, thereby bridging methodological development and practical implementation within the FuturHist digital toolkit.

## 1.3. Overall approach for selection and (re)development of tools

As the FuturHist toolkit is supposed to support users who are not expected to be specialized within all dimensions treated in FuturHist in the early stages of retrofit planning, the tools involved are supposed to be simple, requiring limited input from users. The outcome should support decision and inform the project scope/approach. Tools are not meant to compete with and be more comprehensive than existing, more sophisticated tools as the point is to provide quick results without too much effort.

Important outcomes of using the FuturHist toolkit and the included tools are to gain time in the early decision process, avoid inappropriate interventions, and gain better understanding of which interventions are feasible and their potential performance. There will still be the need for more advanced tools beyond the FuturHist toolkit at a later design stage.

The overall FuturHist strategy was to identify existing, scientifically validated tools and methodologies and redevelop them into a coherent, typology-based decision-support framework for historic building retrofit. Rather than creating new tools from scratch, the project adapted proven resources such as HiBERTool (Eurac Research, 2021), RIBuild (RIBuild, 2020), pyBuildingEnergy (Eurac Research, 2025a), and established LCA, LCC and SRI methodologies. The

selected tools were simplified and restructured to support non-specialist users in the early stages of retrofit planning, requiring limited input while providing sufficiently robust results for decision-making. A central objective was to align all tools with the FuturHist methodology, KPIs and typology-based approach, enabling heritage significance, technical compatibility, energy performance, environmental impacts, life-cycle costs, indoor environmental quality and smart readiness to be assessed within one integrated workflow. This approach balances scientific robustness with usability and makes advanced knowledge accessible to a broader audience without replacing the detailed analyses required during later design stages.

For each dimension, specific approaches, tools and/or educational guides were selected to become part of the FuturHist toolkit, as described in Deliverable D4.1 'Multidimensional decision-making methodology to identify an optimized solution for deep renovation of historic buildings' (Sand, et al., 2026). At a previous stage in the FuturHist project, it was considered to allow users to use their favorite tool as part of the toolkit, addressing the fact that different users use different tools. However, as the toolkit is to be used in the early decision-making stage of a project, to filter between numerous solutions and approaches, it was decided later to implement specific, simplified tools as a part of the toolkit. The implemented tools should be easy to use with a limited amount of input and still give reasonably accurate results, e.g. regarding the energy performance of the building in question after renovation. The user will perform more detailed calculations at a later stage anyway, after choosing a specific package of solutions to implement.

For each of the six dimensions KPIs are defined as reported in Deliverable D1.6 'Assessment categories and KPIs: a multidimensional approach to performance assessment'. As part of describing the methodology of the different tools, it is indicated how they incorporate the KPIs.

## 1.4. Organization of this report

As described in Deliverable D4.1 'Multidimensional decision-making methodology to identify an optimized solution for deep renovation of historic buildings' (Sand, et al., 2026), the FuturHist toolkit operates with six dimensions, covering heritage significance, technical compatibility, energy performance, indoor climate, environmental values and economy. On top of that, the toolkit also includes a decision tree and a smart readiness indicator. Each of these dimensions and functionalities are given a separate chapter in this report presenting one or more tools and/or guides connected to that dimension:

- Chapter 2: Decision-tree logic for filtering solutions
- Chapter 3: Heritage significance
- Chapter 4: Technical compatibility
- Chapter 5: Energy performance
- Chapter 6: Indoor environmental quality

- Chapter 7: Environmental values (LCA)
- Chapter 8: Economy (LCC)
- Chapter 9: Smart Readiness Indicator (SRI)

Each of the chapters 2-9 are structured with subsections for:

- Concept and methodology: Describes the overall concept and methodology of the tool(s), including a justification of the choice of tool(s) and a description of functionalities incl. input/output parameters.
- Development: Describes necessary (re)development of the tool(s) to become part of the FuturHist toolkit and to be aligned with the project approach to energy retrofit/renovation.
- Testing: Describes how the testing was implemented, and why.
- Results and Discussion: Presents and discusses the results of testing the tool(s) and whether this resulted in additional redevelopment or insights to be considered when finalizing the FuturHist toolkit.

Chapter 6 about the IAQ guide is organized a bit differently as explained in the introduction of that chapter.

How these tools and guides are integrated in the FuturHist toolkit is presented in deliverable D4.1 'Multidimensional decision-making methodology to identify an optimized solution for deep renovation of historic buildings' (Sand, et al., 2026) and D4.3 'Digital step-by-step toolkit (draft)'.

Further, the report contains

- Chapter 10: Conclusion and Outlook: Summarizes the principal outcomes achieved in (re)developing and testing the tools supposed to become part of the toolkit.
- Chapter 11: References.
- Chapter 12: Annexes: Annexes include information too detailed to be part of the different chapters, including guides related to technical compatibility and indoor environment quality, input parameters for energy calculations, and LCA and LCC databases.

## 2. Decision-tree logic for filtering solutions

### 2.1. Concept and methodology

The toolkit is designed to support the user in identifying retrofit solutions compatible with a building typology and then selecting the ones matching case-specific preferences and requirements as presented in deliverable D4.1 'Multidimensional decision-making methodology to identify an optimized solution for deep renovation of historic buildings' (Sand, et al., 2026). For this purpose, a decision-tree logic was developed for gradually filtering and ranking retrofitting solutions collected in the lists of passive (envelope and windows retrofit) and active (building systems) solutions (D2.1 'Conservation compatible passive retrofit solutions' and D3.1 'Conservation compatible solutions for HVAC and RES integration in Historic Buildings') based on multidimensional inputs. The process integrates and connects inputs coming from the assessment of heritage impact (Chapter 3) and technical compatibility (Chapter 4) of solutions. The input needed to evaluate the suitability of solutions in these two dimensions arrives from the typology definition and from the user requirements and preferences. In this way the solutions can be progressively filtered through three stages as shown in Figure 1.

First, when a typology is selected from the typology finder (D4.1), typology-related pre-filtering is activated to exclude solutions. Additionally, user input not compatible with the selected typology is removed to avoid collecting unnecessary information from the user. Second, the user can provide additional input based on their requirements and building-specific features. A link to technical compatibility guides and tools (chapter 4) is provided in this step to support the user. Third, after the filtering process, the user is presented with a list of potentially compatible solutions that can be ranked based on user preferences. This ranking considers additional parameters related to sustainability, energy performance and economy.

Ultimately, the user can define a package of compatible solutions by selecting amongst the filtered and ranked active, passive and window solutions. The package of solutions constitutes a retrofit scenario that will be quantitatively analyzed through the assessment tools for energy performance, IAQ, LCA, LCC and SRI (as described in chapters 5 to 9).

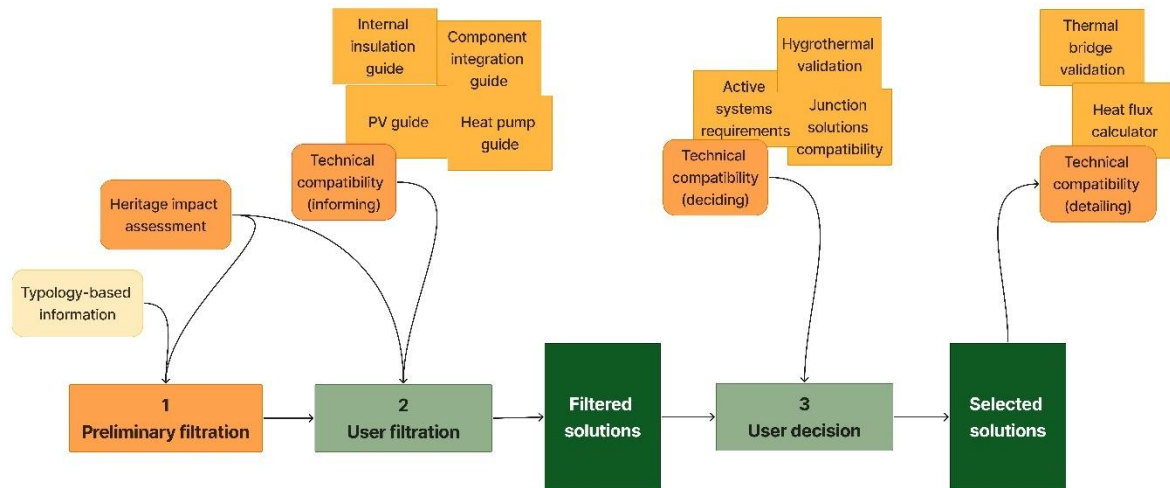


Figure 1. Simplified diagram of the hierarchical logic of the decision tree: inputs from other tools (orange shades), additional typology-based information (yellow), inputs from the user (light green), lists of filtered and selected solutions (dark green).

## 2.2. Development

The filtering logic used in the Historic Building Energy Retrofit Tool (HiBERTool) (Eurac Research, 2021) was selected as a starting point to develop the decision tree logic for filtering solutions in the FuturHist toolkit. HiBERTool already allows users to explore and find different solutions for the energy-efficient retrofit of historic buildings. HiBERTool documents solutions for windows, walls, ventilation, heating and integration of solar technologies and filters them based on answers given by users to a series of questions per category of solutions. This logic was re-developed in FuturHist to include multidimensional aspects of the buildings coming from other parts of the toolkit (heritage impact assessment, technical compatibility, user priorities) and to be applicable at multiple levels (typological and building-specific). In deliverable D2.1 'Conservation compatible passive retrofit solutions' and D3.1 'Conservation compatible solutions for HVAC and RES integration in Historic Buildings', long lists of passive retrofitting solutions (i.e., internal wall insulation, external wall insulation, roof insulation, basement insulation and window retrofit) and active systems solutions were presented; furthermore, for each typology, a short list of typology-compatible solutions was defined. The decision tree logic was developed to bridge the gap between a long list of solutions and building-compatible solutions through typology-based assessments.

First, for each solution category (i.e., internal wall insulation, external wall insulation, roof insulation, basement insulation, window retrofit, active systems), the long and short lists of solutions presented in D2.1 and D3.1 for each typology were compared. The comparison was made to identify a minimum set of parameters potentially usable for filtering and ranking solutions based on building information and case-specific preferences. Second, each filtering or ranking parameter was associated with a specific question. Third, the questions (and associated

parameters) were subdivided into typology-related and user inputs (including building-specific information and user preferences).

The filtering scheme was tested to assess the effectiveness of the filtering logic based on the demonstrator cases. After the testing phase for the filtering logic (described in chapter 2.3), the list of filtering/ranking parameters and the questions were revised. Following this review, a new version of the filtering/ranking logic was developed, and a final dataset of solutions with associated parameters for filtering and ranking was produced to be fed into the toolkit and to be associated with typology-based pre-filtering inputs.

## 2.3. Testing

The filtering logic was tested during a dedicated in-person workshop held in Linköping on May 29<sup>th</sup>, 2026. Participants were divided into four groups representing four demonstrator buildings: Spain, Poland, Sweden and UK-Lister. Each group included at least one person representing the demo owner and one representing the corresponding technical partner.

Excel files associating questions with the tentative list of filtering parameters were provided to each group for the following solution categories: interior insulation, window retrofit and active systems. Each group applied filtering logic by answering the questions and manually applying the filters corresponding to the given answer. In addition, each group was asked to provide feedback on the clarity of questions and the effectiveness of the filtering logic. An example of the workshop results is shown in Table 1.

*Table 1. Sample from the results of the workshop to test the decision tree logic (demonstrator: Linköping, Sweden; filtering of active solutions)*

| Linköping demo                                |                                                                                                                                                     |                                                                                                                                                                                                                         |                                                                                                      |                                                                |                                                                          |
|-----------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|----------------------------------------------------------------|--------------------------------------------------------------------------|
| Questions                                     | What type of heat generation fuel/system is available or can be installed at the demo?                                                              | What type of emission system do you want to install? Or, if you want to keep your current emission system, what is it?                                                                                                  | Do you have technical space available in the building for systems? (e.g. technical rooms, shafts...) | Is it possible to install visible technical elements?          | Which level(s) of disturbance are admitted for the installation?         |
| Instructions                                  | select all filters that match available/compatible fuel/heat generation system                                                                      | select all filters that contain the code of the system you choose                                                                                                                                                       | select all filters that contain the code matching your answer                                        | select all filters that contain the code matching your answer  | select all filters that contain the code matching your answer            |
| Codes for filtering                           | G_W: wood-based<br>G_HP: Heat Pump (air, water, ground)<br>G_G: Gas<br>G_O: Oil<br>G_E: Electricity<br>G_D: District heating<br>G_ST: Solar thermal | E_RF: radiant floor<br>E_RC: radiant ceiling<br>E_RW: radiant walls<br>E_M: mixed systems (not limited to a specific system)<br>E_R: Radiators<br>E_FC: Fan coils<br>E_IU: VRF (variable refrigerant flow) indoor units | S_N: technical space not available<br>S_Y: technical space available                                 | V_N: No<br>V_Y_O: Yes, from outside<br>V_Y_I: Yes, from inside | I_L: low disturbance<br>I_M: medium disturbance<br>I_H: high disturbance |
| Code of the filters applied for each question | G_HP; G_D                                                                                                                                           | E_FC; E_R; E_M                                                                                                                                                                                                          | S_Y                                                                                                  | All                                                            | All                                                                      |

|                                                                                   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                                                                                                                                                                    |                                                                                                                            |                                                                                                                                                |                                                                         |
|-----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------|
| <b>Notes of workshop participants</b>                                             | <i>Would be good to have a separate column regarding local produced electricity (PV-cells) heritage. Separate different heat pumps, since a geothermal heat pump might not be an option even when an air-water heat pump is an option. Energy storage - would be good to be able to sort out that we cannot have energy storage. Some sources are more or less always available (gas, oil, electricity). What is of interest is if for example district heating or geothermal is possible. So maybe ask specifically about this?</i> | <i>It could be better to ask only what kind of distribution system that is in place because the user may not know what he/she wants and therefore exclude to many alternatives</i> | <i>Specify how much space is available. Also there is a difference between shafts and technical room so good to divide</i> | <i>It would be nice to have more options than yes or no (ex "minor" like for the window-section) Should be part of the heritage assessment</i> | <i>Clarification regarding what "disturbance" means in this context</i> |
| <b>Origin of information: typology, demonstrator building or user preference?</b> | <i>Demonstrator building</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | <i>Demonstrator building</i>                                                                                                                                                       | <i>Demonstrator building</i>                                                                                               | <i>Demonstrator building</i>                                                                                                                   | <i>User preference</i>                                                  |

For each case, the results of the process provided a list of filtered solutions that were compared with the solutions identified for the real retrofit scenario for each demonstrator and corresponding typology in WP5. The main outcomes of the testing were:

- For each demonstrator building and corresponding typology, the filtering led to a list of solutions which included the solutions selected for corresponding real retrofit scenario
- For each demonstrator, the list of filtered solutions was shorter than the short list of typology-compatible solutions identified in deliverable D2.1 'Conservation compatible passive retrofit solutions' and D3.1 'Conservation compatible solutions for HVAC and RES integration in Historic Buildings'
- Questions (and corresponding parameters for filtering) were clearly divided into typology-, building- and user preferences-related
- Some tentative filtering parameters were identified as more suitable for ranking (e.g., "preference for prefabricated solutions")
- The clarity of some questions had to be improved to avoid misleading filtering (e.g., improving understanding of "space available for building system components")
- The participants pointed out that some parameters excluded in the tentative list for filtering/ranking are relevant to inform decision-making and should be associated with the solutions in the toolkit to support decision-making (e.g., fire protection class, technical

compatibility information, and prioritization based on existing components conservation condition)

- The question related to the filtering for active systems based on heat generation had to be revised to discourage multiple selection by the user and subsequent ineffective filtering

## 2.4. Results

The decision tree logic was refined after the testing phase and subsequently implemented in the toolkit. The final hierarchy of the decision trees is structured in three subsequent steps shown in Figure 1.

**Step 1. Preliminary filtering:** The outcomes of typology definition and typology-based heritage impact assessment are used to pre-filter solutions based on the selected typology (deliverable D4.1 ‘Multidimensional decision-making methodology to identify an optimised solution for deep renovation of historic buildings’ (Sand, et al., 2026)). This preliminary filtering reduces the input needed from the user of the toolkit by excluding solutions and/or categories of solutions (i.e., internal wall insulation, external wall insulation, roof insulation, basement insulation, windows retrofit and active systems) which are not compatible with the selected typology. Furthermore, the preliminary filtering also removes user questions not applicable to the selected typology.

**Step 2. User filtering:** The user of the toolkit is asked a series of questions to narrow down all pre-filtered typology-compatible solutions based on specific features of the building, actual implementation constraints and personal requirements. The series of questions is tailored to the pre-filtering step described above to match only compatible solution categories and typologically relevant follow-up questions about heritage impact (see Chapter 3.4). To answer technical questions, the user can refer to the guides provided to get information on technical compatibility (see Chapter 4.2.1). If no typology was selected, the pre-filtering is not activated; therefore, the user is asked all filtering questions. In this case, the user must perform heritage impact assessment and technical compatibility assessment for the building and answer all questions autonomously.

**Output 1. Filtered solutions:** All filters identified in step 1 and 2 are activated, and a list of potentially compatible solutions is presented to the user. Each solution is associated with expandable information icons containing additional information and/or warnings related to technical compatibility (chapter 4). At this stage, if a typology was previously selected, the solutions which are part of the typology-based ideal scenario (see ‘Abbreviations and definitions’ section) for whole retrofitting are highlighted.

**Step 3. User decision:** The user can then select their preferred method(s) to rank filtered solutions based on different priorities (e.g. enhance recyclability potential, affordability ...) and further filter solutions based on additional technical compatibility issues (chapter 4.2.2) which are

relevant for decision-making (i.e., hygrothermal validation, requirements of active system, junction solutions compatibility) and/or compliance with corresponding typology-based ideal retrofit scenario.

**Output 2. Selected solutions:** The decision tree ends when the user selects the solution(s) for the retrofitting scenario to be assessed using the subsequent tools of the toolkit. Once the user selects a solution from the filtered lists, it is added to the retrofit scenario that is connected to the subsequent tools of the toolkit. At this step, the user also has the opportunity to further explore technical compatibility via additional resources for detailing solutions (see Chapter 4.3.3).

To visualize the functioning of the logic integrated in the digital toolkit, one full branch of the decision tree for internal wall insulation is presented in detail with inputs matching the Spanish demonstrator case (Figure 2, Figure 3, Figure 4, Figure 5). In each figure, inputs from other tools are presented in orange shades, additional typology-based information in yellow, inputs from the user in light green and lists of filtered and selected solutions in dark green.

For each solution category, the questions and parameters for filtering integrated in the toolkit are listed below (Table 2, Table 3, Table 4, Table 5, Table 6). Table 7 shows all ranking parameters included in the system by solution category. Definition of all mentioned parameters is included in deliverable D2.1 'Conservation compatible passive retrofit solutions' and D3.1 'Conservation compatible solutions for HVAC and RES integration in Historic Buildings'. Filtering of solutions based on heritage significance is explained in detail in Chapter 3; the details of technical compatibility tools, sources used for additional filtering, ranking and selection are presented in Chapter 4.

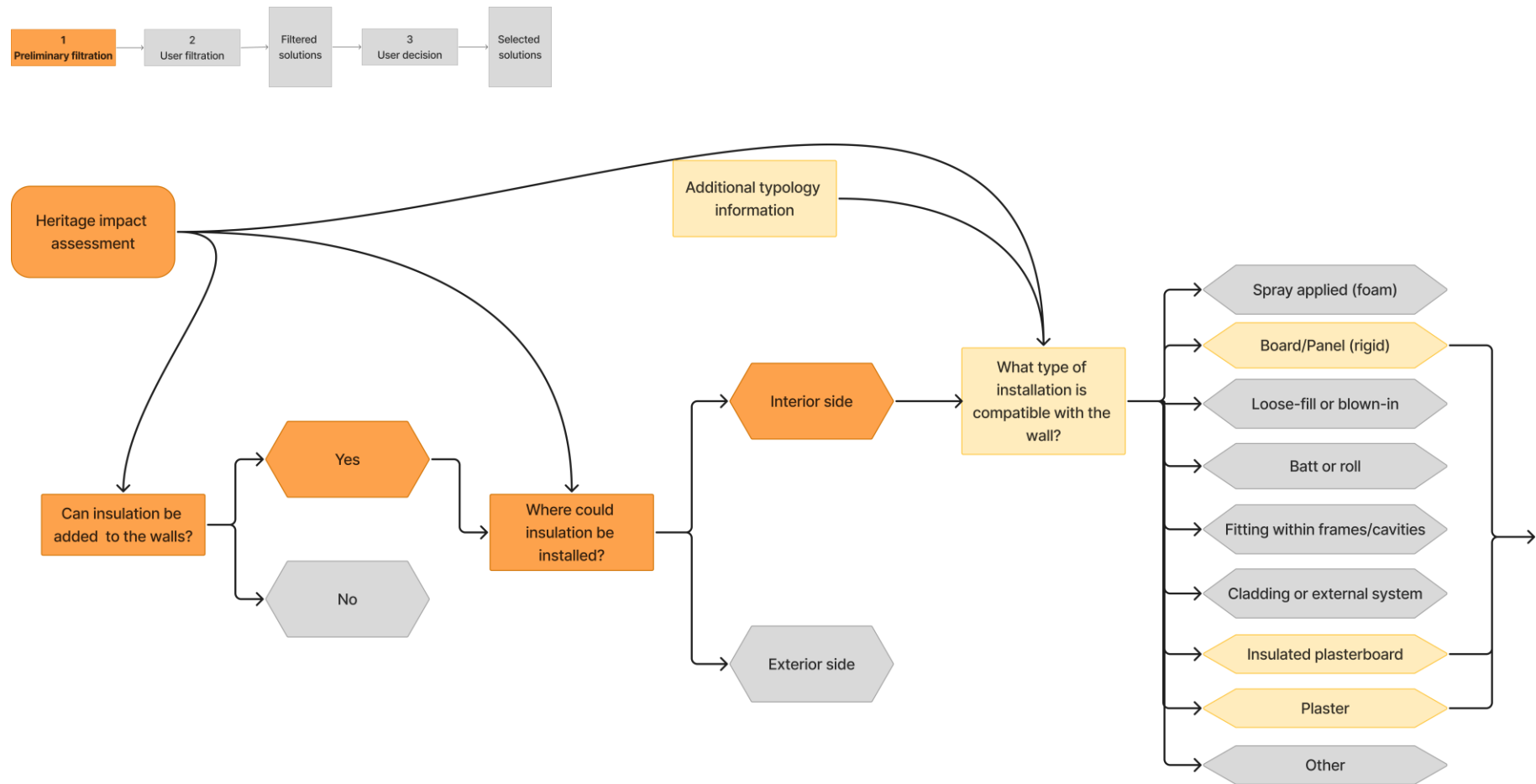


Figure 2. Visualization of full branch of the decision tree for internal wall insulation with inputs matching the Spanish demonstrator case; step 1: preliminary filtering based on typology heritage impact assessment and typology-based information. Inputs from other tools (orange shades), additional typology-based information (yellow).

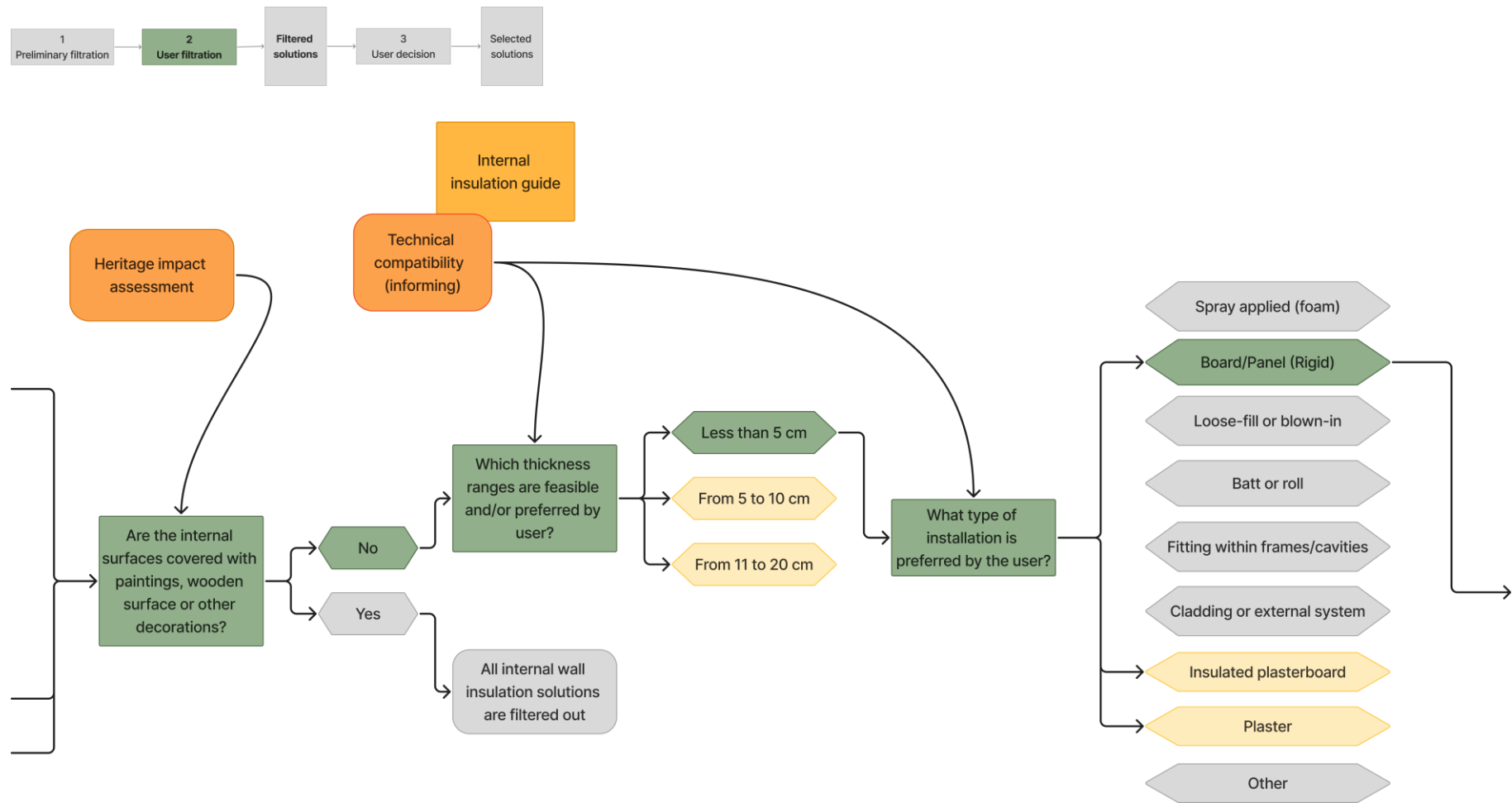


Figure 3. Visualization of full branch of the decision tree for internal wall insulation with inputs matching the Spanish demonstrator case; step 2: user filtering. Color legend: inputs from other tools (orange shades), additional typology-based information (yellow), inputs from the user (light green).

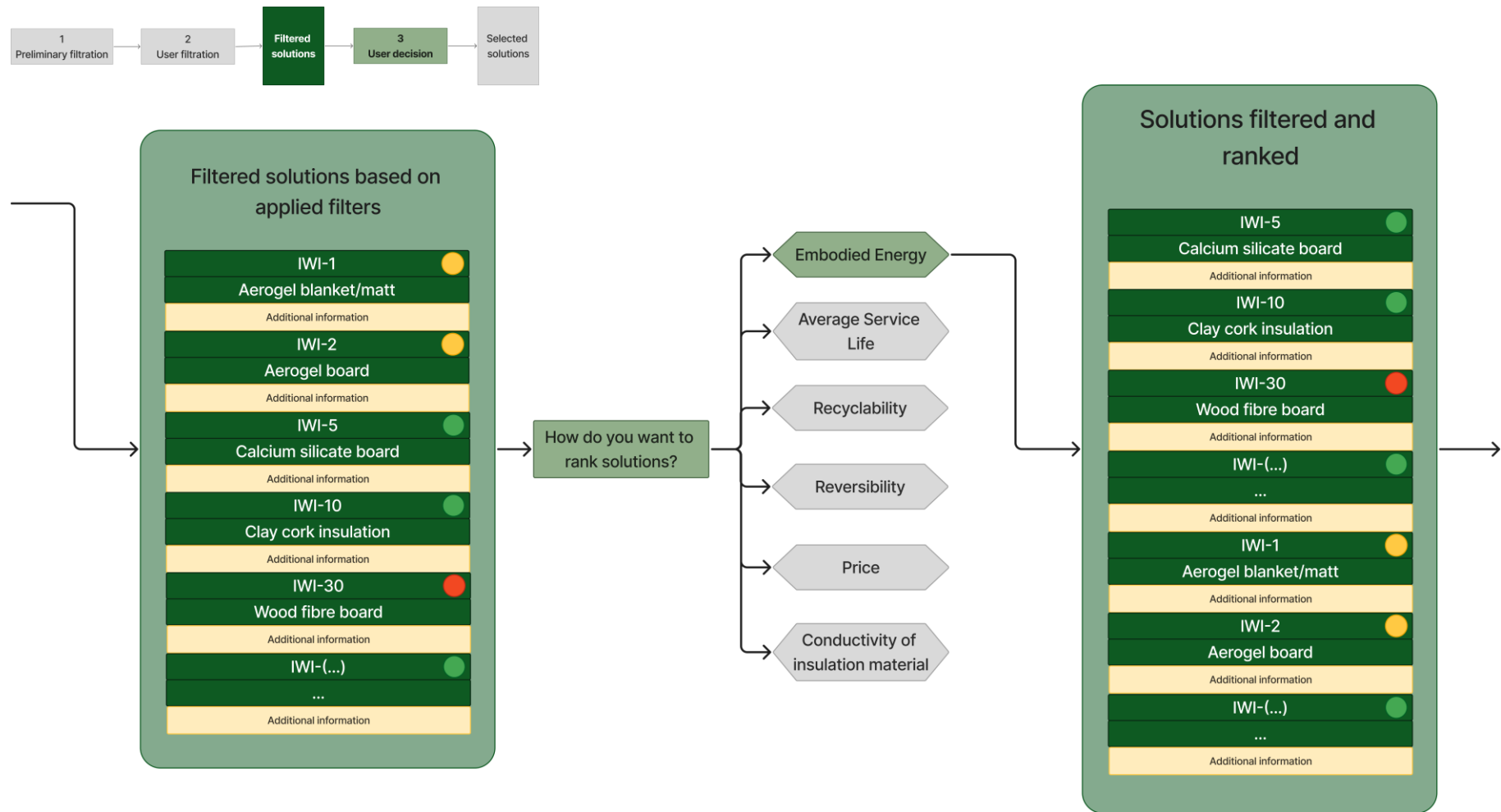


Figure 4. Visualization of full branch of the decision tree for internal wall insulation with inputs matching the Spanish demonstrator case; -output1 and step 3: filtered solutions and solution ranking. Green/yellow/red dots represent the status of currently available hygrothermal pre-validation (see chapter 4.2.2). Color legend: inputs from other tools (orange shades), additional typology-based information (yellow), inputs from the user (light green), lists of filtered and selected solutions (dark green).

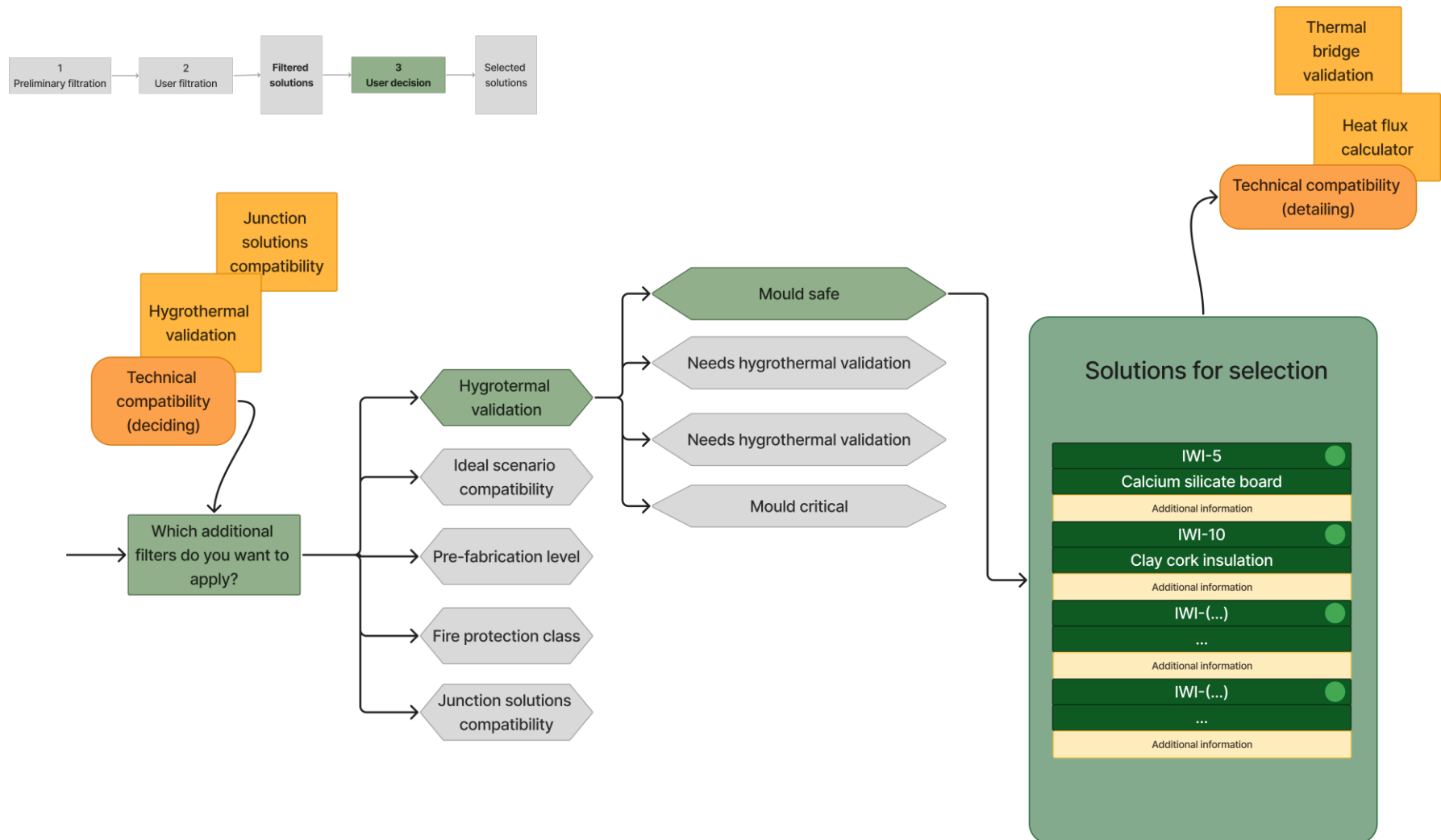


Figure 5. Visualization of full branch of the decision tree for internal wall insulation with inputs matching the Spanish demonstrator case; step 3: filtered solution ranking and additional filtration before selection. Green/yellow/red dots represent the status of available hygrothermal pre-validation (see chapter 4.2.2). Color legend: inputs from other tools (orange shades), additional typology-based information (yellow), inputs from the user (light green), lists of filtered and selected solutions (dark green).

Table 2. Filtering parameters and questions for internal and external insulation solutions.

| Filtering parameters | Questions                                                     | Possible answers                      |
|----------------------|---------------------------------------------------------------|---------------------------------------|
| <b>Thickness</b>     | Which thickness ranges are feasible and/or preferred by user? | Multiple choice of thickness ranges   |
| <b>Installation</b>  | Which type of installation is preferred by the user?          | Multiple choice of installation types |

Table 3. Filtering parameters and questions for roof insulation solutions.

| Filtering parameters | Questions                                                         | Possible answers                       |
|----------------------|-------------------------------------------------------------------|----------------------------------------|
| <b>Thickness</b>     | Which thickness ranges are feasible and/or preferred by user?     | Multiple choice of thickness range     |
| <b>System type</b>   | In which part of the roof do you want to/ can you put insulation? | Multiple choice of system types        |
| <b>Application</b>   | Where do you want to/can you apply insulation?                    | Multiple choice of construction layers |
| <b>Installation</b>  | Which installation type is preferred by the user?                 | Multiple choice of installation types  |

Table 4. Filtering parameters and questions for basement insulation solutions.

| Filtering parameters | Questions                                                     | Possible answers                       |
|----------------------|---------------------------------------------------------------|----------------------------------------|
| <b>Thickness</b>     | Which thickness ranges are feasible and/or preferred by user? | Multiple choice of thickness ranges    |
| <b>Application</b>   | Where do you want to/can you apply insulation?                | Multiple choice of construction layers |
| <b>Installation</b>  | Which installation type is preferred by the user?             | Multiple choice of installation types  |

Table 5. Filtering parameters and questions for window retrofit solutions.

| Filtering parameters            | Questions                                                                      | Possible answers                           |
|---------------------------------|--------------------------------------------------------------------------------|--------------------------------------------|
| <b>Type of windows</b>          | What type of windows are there in the building?                                | Multiple choice of window type             |
| <b>Elements to be preserved</b> | Are parts of the windows original and should be preserved?                     | Multiple choice of window elements         |
| <b>Visual impact</b>            | Can the solution be visible from inside   outside   neither side   both sides? | Multiple answer with visual impact options |
| <b>Space availability</b>       | Is there space inside/outside to add layers?                                   | Multiple answer with space availability    |

Table 6. Filtering parameters and questions for active systems solutions.

| Filtering parameters                | Questions                                                                                                                            | Possible answers                                         |
|-------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------|
| <b>Heat generation</b>              | What is/are the possible/preferred type of heat generation?                                                                          | Multiple choice of heat generators                       |
| <b>Emission type</b>                | What is/are the possible/preferred type of emission system?                                                                          | Multiple choice of emission systems                      |
| <b>Technical space availability</b> | Is there any technical space (e.g. technical rooms, basements, shafts, space on roof or in courtyards...) available in the building? | Multiple choice of space availability                    |
| <b>Visibility</b>                   | Is it possible to install visible technical elements?                                                                                | Multiple choice of visual impact                         |
| <b>Installation disturbance</b>     | Which level(s) of disturbance to the occupants is/are permitted/preferred for the installation?                                      | Multiple choice of level of disturbance to the occupants |

Table 7. Ranking parameters applicable to filtered solutions by category.

| Parameters                                                     | Categories                                                                                                      | Ranking criteria                                |
|----------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|-------------------------------------------------|
| <b>Thermal conductivity of insulation material</b>             | Internal insulation, external insulation, roof insulation, basement insulation                                  | Value of thermal conductivity                   |
| <b>U-value of window</b>                                       | Window retrofit                                                                                                 | Value of thermal transmittance                  |
| <b>Embodied energy</b>                                         | Internal insulation, external insulation, roof insulation, basement insulation, window retrofit                 | Embodied energy category (3 levels)             |
| <b>Average lifetime</b>                                        | Internal insulation, external insulation, roof insulation, basement insulation                                  | Average service life duration (3 levels)        |
| <b>Recyclability</b>                                           | Internal insulation, external insulation, roof insulation, basement insulation                                  | Recyclability potential (3 levels)              |
| <b>Prefabrication</b>                                          | Internal insulation, external insulation, roof insulation, basement insulation                                  | Prefabrication category (3 levels)              |
| <b>Reversibility</b>                                           | Internal insulation, external insulation, roof insulation, basement insulation, window retrofit                 | Reversibility potential (3 levels)              |
| <b>Cost</b>                                                    | Internal insulation, external insulation, roof insulation, basement insulation, window retrofit, active systems | Cost category (3 levels)                        |
| <b>Priority based on current condition of existing windows</b> | Window retrofit                                                                                                 | Current condition of windows (multiple options) |

## 3. Heritage significance

### 3.1. Concept and methodology

The heritage methodology implemented in the FuturHist toolkit does not replace a full heritage significance assessment, nor the statutory procedures that may be required for protected buildings. Its purpose is more limited and operational: to provide a filtering of retrofit solutions by identifying likely heritage vulnerabilities and likely impacts within the FuturHist typologies.

The tool should help distinguish between measures that are broadly compatible, measures that require adaptation or further investigation, and measures that should normally be avoided. The methodology is situated within a values-based conservation framework. In such a framework, decisions about change are not based merely on the physical condition or technical performance of a building, but on an understanding of why the building matters, which physical elements contribute to that significance, and how proposed changes may affect significance. This follows a widespread approach in heritage management, considered a mandatory requirement amongst heritage experts, where the first step is to understand the place and its values before deciding how it should be managed (Bond & Worthing, 2016), (Avrami, et al., 2019).

The FuturHist toolkit deliberately avoids asking the user to carry out a comprehensive heritage significance assessment. A full value assessment is an expert-led activity and can be complex. It may involve historical research, architectural analysis, assessment of authenticity and integrity, understanding of how to identify and categorize values etc. These assessments are also shaped by national traditions, professional cultures and the specific context of each building. If this complexity was built into the toolkit, the assessment would be too demanding for the intended use: the user would need to make interpretative judgements that require specialist expertise. Additionally, whilst the purpose of FuturHist is to develop a typology-based approach to support energy retrofit of historic buildings, there may be some variations of heritage values between two buildings of the same typology; a specific analysis of the targeted building may be required.

The methodological choice in FuturHist is therefore to work from a values-based starting point, but to operationalize it through a simplified heritage impact approach. Rather than asking the user to define the significance of the building or its parts, the tool focuses on the likely consequences of individual retrofit measures for those elements that are relevant for the typology and the proposed intervention. This follows the direction of EN 16883 (European Committee for Standardization (CEN), 2017a), where the assessment of retrofit solutions includes attention to how measures may affect heritage significance through material, visual and spatial impacts. A simplified heritage impact approach also implies a higher potential for replicability for buildings of the same typology, supporting a typology-based approach.

This shift from value assessment to impact assessment is central to the usability of the tool. The broader value discussion remains the conceptual background, but the practical assessment is not delegated to the user. The methodology is an extension of earlier tools such as the Responsible Retrofit Guidance Wheel (Carmona, et al., 2012) (which incorporates generic assessments of impacts of solutions in relation to the degree of statutory protection of the building) and EFFESUS (Effesus, 2024). In FuturHist, expert-derived typology information about vulnerability to impacts is built into the system: the toolkit already contains assumptions about which building elements are likely to be character-defining and sensitive to change. For example, in the Swedish typology *Flerbostadshus*, interiors are generally considered less vulnerable to material interventions, whereas façades are typically more sensitive to visual change due to the architectural characteristics associated with modernist design. The user's role is therefore not to decide what has heritage value, but to provide factual information that can refine the filtering: whether the relevant element is present, whether it appears to be original or replaced, whether it has been altered, whether it is in poor physical condition, and whether there are obvious case-specific circumstances that differ from the typology description. The tool then combines this user input with the embedded typology assessment and the impact of the proposed measure. In this way, the user is asked for information about the building, not for a comprehensive heritage assessment.

A central design choice is that the user is not expected to assess every element of the building. Each FuturHist typology instead contains a minimum set of heritage-related questions needed for the first filtering of solutions. The number and content of these questions depend on the typology and on the building elements most likely to be affected by common retrofit measures. The user can then refine the filtering by adding further information about the specific building. A typology may indicate that a certain feature is normally significant, but the specific building may have been altered, repaired, damaged or partly reconstructed. The tool therefore combines typology-based expert assumptions with case-specific descriptive input.

The distinction between legal protection and heritage value is important. A building can have heritage value without being formally protected, and a protected building may contain elements of different levels of vulnerability. Furthermore, the regulation and conservation practices differ within the EU member states and the UK. The tool therefore treats legal protection as contextual information to the user, while the filtering itself is based on the embedded typology assessment, the user's factual input, and the likely impact of the proposed measure. Doing so also helps simplify the heritage impact assessment process for the user. Importantly, it ensures that this process is potentially applicable to any building in Europe, irrelevant of national or regional legislation.

Consequently, the FuturHist toolkit is not bulletproof against suggesting retrofit solutions that may conflict with specific features of a building that should be protected from alteration, as it is intended as an early-stage decision-support toolkit. Users will be warned of this limitation and will always be advised to seek professional guidance from a heritage expert regarding the specific listing status of both the building and the area, as well as any relevant regulations.

The FuturHist Heritage Assessment framework distinguishes between three different kinds of impacts from interventions:

**Material impact** is the effect of a measure on the historic fabric itself: original materials, construction layers, craftsmanship, finishes, patina, joinery, fixtures and evidence of age or use. It concerns what is removed, replaced, drilled through, covered, sealed, or altered. A measure can have low visual impact but still high material impact if it destroys significant fabric.

**Visual impact** is the effect of a measure on how the building is perceived: its appearance, character, proportions, details, surfaces, façade composition, interior design, light conditions etc. It concerns whether the intervention is visible and whether that visibility changes the significance of the building or its setting.

**Spatial impact** is the effect of a measure on the building's spatial configuration: room proportions, plan layout, circulation, hierarchy of spaces, ceiling heights, wall thickness, openings, thresholds and the legibility of historic use. This includes changes such as subdividing rooms, lowering ceilings, adding service voids, increasing thickness of internal walls, changing construction details from thicker construction material such as insulation up to alteration of the shape of a roof, or the addition of technical equipment that will take space inside or outside a building, or changing the relationship between rooms.

## 3.2. Development

The core principle of the FuturHist Heritage Impact Assessment Framework is to assess the generic heritage impacts of retrofit solutions and relate these to the vulnerabilities of specific elements within each typology.

### Vulnerability in building elements

A building element is a commonly recurring part of a building typology, such as a feature or a construction detail. Elements may carry heritage significance and can therefore be vulnerable to change. Through a series of workshops, ERIK, UU, and heritage partners from each country identified the relevant elements for each typology and defined their corresponding material, visual, and spatial vulnerabilities to change. The mapping logic is illustrated in Figure 6.

The elements are mapped within building component categories, which are the same across the typologies: Roof, Façade, Windows, Foundation & Basement, Interior, Installations and Setting & Site.

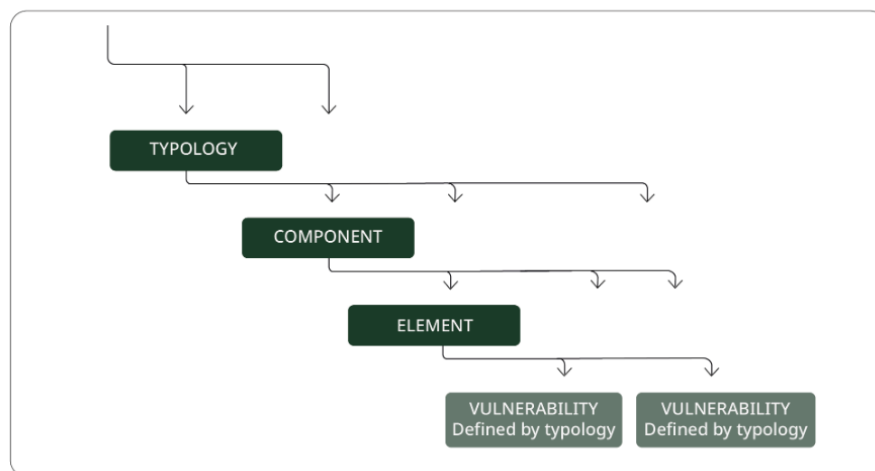


Figure 6. Mapping logic of vulnerabilities in typologies.

A simplified vulnerability scale is used for the expert-led assessment of typologies. Elements that contribute to the heritage significance of a typology are assigned a vulnerability rating of high, medium or low. The rating reflects a combined assessment of two factors: the significance of the element to the heritage character of the building and its sensitivity to alteration through retrofit measures. A building element that is both important to the building’s heritage significance and sensitive to change is considered highly vulnerable. A medium-vulnerability element is significant, but some forms of alteration may be compatible with its heritage characteristics. An element with low vulnerability still requires consideration, but its heritage significance and/or sensitivity to change allows greater scope for adaptation.

This scale does not claim to provide a comprehensive assessment of heritage value. Rather, it is a practical means of translating likely heritage significance and sensitivity to change into filtering rules for retrofit solutions. The latter is based on subcategories of solutions that have been identified in FuturHist for passive solutions, active systems, and windows. In essence, it is a way to connect a significant amount of heritage compatible solutions quickly and in a reliable manner. Figure 7 shows an example of expert-led assessments of vulnerabilities for the Swedish typology “Monumentalbyggnad”.

| Elements in typology      |                                               | Vulnerabilities |        |         |
|---------------------------|-----------------------------------------------|-----------------|--------|---------|
| Monumentalbyggnad (SK1)   |                                               | Material        | Visual | Spatial |
| <b>Component: Roof</b>    |                                               |                 |        |         |
| <b>Attic</b>              |                                               |                 |        |         |
| Timber roof structure     | Large-span timber trusses                     | Medium          | Medium | Low     |
| Iron/steel roof structure |                                               | High            | Medium | Low     |
| <b>Pitch</b>              |                                               |                 |        |         |
| Steep pitched roof        | Dominant roofscape, often visible from street | High            | High   | Medium  |
| <b>Surface</b>            |                                               |                 |        |         |
| Metal roofing             | Copper or iron sheets, high craftsmanship     | High            | High   | Low     |
| Clay tiles                | Hand made clay tiles                          | High            | High   | Low     |
| Roof decorative features  | Towers, ridges, dormers                       | High            | High   | Low     |
| Chimneys                  | Often high, decorative and dominating         | High            | High   | Low     |

Figure 7. Example of a mapping of elements and their vulnerabilities within a typology.

## Impacts of retrofit solutions

The FuturHist solutions have impacts within the three heritage impact categories to varying degrees (low, medium, high). These impacts have been assessed, and it has been defined which elements in the typology they affect (see

| Code  | Solution name                                        | Heritage Impact: Material | Heritage Impact: Visual | Heritage Impact: Spatial | Heritage Impact: Reversibility | Heritage Assessment Component | Elements in 01 casa de pisos       | Elements in 02 Kamienica | Elements in 05 Monumentalby nad | Elements in 08 Georgian Tenement |
|-------|------------------------------------------------------|---------------------------|-------------------------|--------------------------|--------------------------------|-------------------------------|------------------------------------|--------------------------|---------------------------------|----------------------------------|
| RI-14 | Mineralised fir wood wool bound with Portland cement | Medium                    | Medium                  | High                     | No                             | Roof                          | "surface"                          | "shape"<br>"finish"      | "Pitch"<br>"Surface"            | "Shape of the roof"              |
| RI-15 | Wood fibre (outside)                                 | Medium                    | Medium                  | High                     | No                             | Roof                          | "surface"                          | "shape"<br>"finish"      | "Pitch"<br>"Surface"            | "Shape of the roof"              |
| RI-16 | Wood fibre/wood wool (inside)                        | High                      | High                    | High                     | Yes                            | Roof                          | "Wooden beams visible from inside" | "Structure"              | "Attic"                         | "Timber roof truss"              |

Figure 8). If several elements are affected, the element(s) with the highest vulnerability are chosen (Figure 9).

| Code  | Solution name                                        | Heritage Impact: Material | Heritage Impact: Visual | Heritage Impact: Spatial | Heritage Impact: Reversibility | Heritage Assessment Component | Elements in 01 casa de pisos       | Elements in 02 Kamienica | Elements in 05 Monumentalby nad | Elements in 08 Georgian Tenement |
|-------|------------------------------------------------------|---------------------------|-------------------------|--------------------------|--------------------------------|-------------------------------|------------------------------------|--------------------------|---------------------------------|----------------------------------|
| RI-14 | Mineralised fir wood wool bound with Portland cement | Medium                    | Medium                  | High                     | No                             | Roof                          | "surface"                          | "shape"<br>"finish"      | "Pitch"<br>"Surface"            | "Shape of the roof"              |
| RI-15 | Wood fibre (outside)                                 | Medium                    | Medium                  | High                     | No                             | Roof                          | "surface"                          | "shape"<br>"finish"      | "Pitch"<br>"Surface"            | "Shape of the roof"              |
| RI-16 | Wood fibre/wood wool (inside)                        | High                      | High                    | High                     | Yes                            | Roof                          | "Wooden beams visible from inside" | "Structure"              | "Attic"                         | "Timber roof truss"              |

Figure 8. Example of heritage impact assessment of solutions and the elements they impact on.

|        | Low | Medium | High |
|--------|-----|--------|------|
| Low    | ✓   | ✓      | ✓    |
| Medium | ✓   | ⚠      | ⚠    |
| High   | ✓   | ⚠      | ✗    |

Figure 9. Filtering logic when combining the heritage vulnerabilities of the elements in typologies and heritage impacts of solutions.

If either vulnerability or impact is low, the solution will not be filtered out for heritage reasons. Higher levels of vulnerability and impact may trigger a warning, a follow-up question, or the exclusion of the solution. Where high vulnerability to change coincides with high impact in any one of the material, visual, or spatial categories, the solution is filtered out for the relevant typology.

The heritage impact assessment therefore produces two outputs: a filtered list of solutions based on the selected typology, and a short list of follow-up questions. The user answers to these questions support the second filtering of solutions during the baseline assessment.

### 3.3. Testing

Testing the FuturHist heritage impact assessment framework is two-folded; testing the resulting filtering of solutions and user questions, and testing whether the implementation into the digital toolkit works. For the latter part, tested within ERIK and in UIBK, the result is positive as the heritage framework in the current version of the toolkit results in filtration of the solutions.

This chapter describes how FuturHist partners have tested the logic of the framework and resulting filtering of solutions for the first four typologies (Casa de pisos in Spain, Kamienica in Poland, Monumentalbyggnad in Sweden and Georgian Tenement in the United Kingdom).

ERIK has facilitated a series of meetings with relevant project partners within FuturHist that have experience with the heritage significance of each typology. In each meeting, the lists of elements and their vulnerabilities – results from prior workshops with the same partners – were summarized while the list of solutions and whether they are excluded, followed by warnings or considered acceptable, was presented. For the solutions that depend on a follow-up user question, the questions were formulated. For Casa de Pisos, AVRA and EURAC have reviewed the results, PK for Kamienica, UU for Monumentalbyggnad and EWH for Georgian Tenement.

Overall, the approach has been successful in that the partners found the framework appropriate for its purpose, and the filterings and user questions were found suitable for the typologies, with only a few remarks:

#### Casa de Pisos

- This typology does not typically have cavity walls, so the solution *EWI-2 Cavity wall insulation with insulation granulate* is changed from acceptable to excluded.
- The first heritage assessment did not take the values of the ceilings into account in a satisfactory way; indeed, these can have high heritage significance in Casa de Pisos and therefore limit possible solutions affecting the interior. A user question “*Is it possible to put insulation between the roof beams, or should they remain visible?*” was added.
- It was discussed whether external wall insulation is realistic, and it was agreed that in case the facade is covered with coloured plaster, a thin layer of external insulation can be added, but with the caveat that it should be clearly emphasized that the thickness of this solution cannot exceed the plinth.

### Kamienica

- There are not always cavity walls in Kamienica, and the user should at some point be asked to check if the solution *EWI-2 Cavity wall insulation with insulation granulate* is possible.
- When combining the heritage impact assessment of the material, visual and spatial vulnerabilities of the windows and compared with the impacts from the solutions, adding new layers to the inside of the window is ruled out. Even though this matches most practices, PK wanted to leave room for these solutions to be considered, hence solutions *2C1d Add a double insulating glazing to upgrade the existing single to a coupled window* is changed from excluded to acceptable, but with a warning.

### Monumentalbyggnad

- This typology does not typically have cavity walls, so the solution *EWI-2 Cavity wall insulation with insulation granulate* is changed from acceptable to excluded.
- According to the heritage impact assessment, the solutions that change glazing should be ruled out if the glazing is original. EURAC found this problematic, as we should never completely rule out changing glazing, as this might be necessary regardless of heritage values, and it was decided to change this filtration.

### Georgian Tenement

- This typology does not typically have cavity walls, so the solution *EWI-2 Cavity wall insulation with insulation granulate* is changed from acceptable to excluded.
- The solutions *BFI-13 Mineral wool under the ceiling* and *BFI-15 Polystyrol/EPS/XPS under the ceiling* should be excluded for this typology. This is not because of heritage issues, but simply because it came up during the testing meeting, that it is not meaningful to put insulation here as the basement is inhabited.

## 3.4. Results and discussion

The FuturHist Heritage Impact Assessment Framework demonstrates how heritage considerations can be translated into an operational method for early-stage retrofit decision-making. Its main contribution is not to replace established heritage assessment procedures, but to integrate heritage impact considerations in a simplified way early in the planning process when retrofit options are still open and can be redirected. The tool has similarities with previous decision-support framework/tools such as EFFESUS (Effesus, 2024), the Responsible Retrofit Guidance Wheel (Carmona, et al., 2012), HIBERtool (Eurac Research, 2021) and other guidance systems reviewed in deliverable D1.4 'Selection of tools: a review of guidelines and tools for energy retrofits in historic buildings' (Hupkes, et al., 2025). Like these tools, it uses structured

questions to support risk-aware decision-making for historic buildings. The specific contribution of FuturHist is the use of typologies with embedded expert-derived heritage impact assessments (and a set of typology-specific minimum questions as a starting point for filtering), as well as the integration of the heritage impact assessment in a holistic decision-support toolkit. As a result, the framework allows heritage considerations to inform the first selection of retrofit measures without requiring a full heritage significance assessment.

The framework is based on a deliberate simplification of values-based conservation practice. Rather than asking users to identify and evaluate heritage significance themselves, the tool uses typology-based assumptions about which building elements are likely to be sensitive to change. These assumptions are combined with the expected material, visual, and spatial impacts of retrofit solutions. The result is a structured filtering process that distinguishes between measures that are broadly compatible, measures that require further information or adaptation, and measures that should normally be avoided for heritage reasons.

This approach has several strengths. It makes it easier to include heritage considerations in early-stage energy retrofit planning without requiring users to have specialist expertise in heritage assessment. Users who are not heritage professionals are asked to provide information about the building, such as whether a certain element is present, rather than to make judgements about heritage significance. The two-step filtering process allows the toolkit to combine generic expert knowledge at a typology level with building-specific refinement. This reduces the risk that the assessment becomes either too general or too demanding for early-stage use. Finally, the framework enables a degree of consistency across the FuturHist typologies, as similar kinds of impacts and vulnerabilities are assessed through a common logic.

At the same time, the framework has limitations. Heritage significance is always context-dependent and cannot always be reduced to predefined elements or fixed categories. A typology-based assessment may overlook unusual features, later alterations that have acquired significance or specific legal requirements. Applying the methodology across different countries, and therefore jurisdictions, also introduces challenges, as terminology, concepts of heritage significance, and approaches to heritage assessment vary between countries and regulatory contexts. Conversely, it may filter out measures that could be acceptable in an individual building where the vulnerable element is absent, already replaced or of limited significance. Mitigation measures can be taken to limit this phenomenon, by asking for information about the building to provide more context. However, this is limited to ensure the tool remains easy and quick to use. The framework should therefore be understood as a precautionary decision-support tool, not as a substitute for professional judgement, statutory consent procedures or a full heritage significance assessment.

Dealing with protected and non-protected historic buildings when implementing a heritage impact assessment is challenging. The different degrees of protection of historical buildings varies from none to severe restrictions on energy retrofit interventions. Therefore, the heritage impact assessment framework was applied to the four typologies by considering the buildings

had the lowest degree of protection. This allows a broader range of solutions to be prefiltered after the selection of the relevant typology. Follow-up user question(s) is (are) then asked for combinations of vulnerability and solution impact that have been identified as source of concern or requiring more information.

The type of approach chosen in FuturHist, in terms of degree of adhesion to heritage principles (and heritage requirements), has major consequences on results when experts assess the degree of vulnerability of building elements and the impact of retrofit solutions. It was decided to embrace an approach that follows heritage principles without being too strict, to allow more retrofit solutions not to be filtered out – leaving more freedom to the user to make decisions on these solutions. FuturHist has adopted the principle to protect heritage elements of the building that are characteristic to the related typology. Follow-up user questions also help refine the degree of heritage requirements for the building being assessed, depending on whether it is listed or not. Additionally, the application by expert of the approach chosen to perform the heritage impact assessment for each building typology should be consistent to avoid discrepancies between typologies of different countries. The type of approach chosen in FuturHist should also be consistently applied by experts in each typology/country.

The framework also highlights a broader methodological challenge in heritage-sensitive retrofit planning. Energy retrofit decisions often rely on predefined technical criteria and quantifiable performance measures, while heritage assessment depends on interpretation, context and professional judgement. The FuturHist approach addresses this tension by translating likely heritage vulnerabilities and impacts into practical filtering rules, while still acknowledging that the final assessment of a specific building must remain open to expert review. In this sense, the tool does not resolve the complexity of heritage values, but it makes them actionable within the early stages of a wider retrofit decision process without expert knowledge. As a result, it contributes to mainstreaming them for any retrofit project, irrelevant of the degree of heritage protection (including none) of the targeted historic building.

## 4. Technical compatibility

Chapter 4 presents the approaches and resources developed to assess the technical compatibility of retrofit solutions for historic buildings, guiding users from initial understanding and feasibility screening to more detailed validation and design support within the FuturHist toolkit. As presented above, part of these resources is directly linked to the decision-tree logic for filtering solutions discussed in chapter 2.

### 4.1. Concept and methodology

To characterize the technical compatibility of solutions, different decision-support resources were developed to become part of the FuturHist toolkit. These elements were both newly developed within the FuturHist project and adapted from previous research projects like (RIBuild, 2020). The material developed for FuturHist's toolkit included:

- A step-by-step guide for architects and consultants on internal insulation based on the results of the RIBuild project. It guides the users through different decision-making stages and helps them describe the present condition of the building envelope.
- Two guides for architects on the integration of photovoltaic and heat pumps in historic buildings resulted from the work carried on in Work Package 3 “Active systems for a clean energy transition”.
- A set of precalculated hygrothermal simulations carried out to provide the user with a tailored compatibility evaluation of internal insulation for specific typologies.
- A set of rules for an initial technical feasibility assessment of active systems based on indicators related to water temperature, power supply, and space availability to be applied to the cases featuring a heat pump system.
- Qualitative and quantitative information for the integration of components in the building envelope with particular attention to airtightness, protection against driving rain and rising damp, and the risks of condensation and mould growth at thermal bridges
- An interactive tool to elaborate on the results of heat flux measurements developed to help more advanced users to analyse the data gathered in a more intuitive way while being guided through the normative checks of the ISO 9869-1:2014.
- A simplified method for determining Smart Readiness Indicator (SRI) derived from EPBD (European Parliament and Council, 2018) adapted and integrated into the toolkit workflow.

All these resources are of different nature, serve different purposes and could eventually be used by users with different levels of understanding and responsibility in the project. The resources were therefore organised into three categories according to their phase and purpose: from general guidance to feasibility screening, and to detailed technical validation, cf. Table 8.

Table 8. Technical compatibility resources in the FuturHist toolkit.

|                                                 | Purpose                                                                                                                                                    | Resources                                                                                                                                                       |
|-------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>1. Information tools: section 4.2.1</b>      | Provides guidance and background knowledge to support early understanding and design decisions.                                                            | Internal insulation guide (4.2.1.1);<br>Component integration guide (4.2.1.2);<br>Photovoltaics guide (4.2.1.3);<br>Heat pump guide (4.2.1.4)                   |
| <b>2. Decision-support tools: section 4.2.2</b> | Supports early feasibility checks and filters solutions according to typology, hygrothermal safety, component integration, and active-system requirements. | Internal insulation hygrothermal validation (4.2.2.1);<br>Component integration in typologies (4.2.2.2);<br>Technical requirements for active systems (4.2.2.3) |
| <b>3. Detailing tools: section 4.2.3</b>        | Supports more detailed technical validation once a solution has passed the first filtering stage.                                                          | Thermal bridges validation (4.2.3.1)<br>Heat flux calculator (4.2.3.2)                                                                                          |

In addition to that, SRI is presented separately in Chapter 9 as it is integrated elsewhere in the toolkit and follows a logic of evaluation of scenarios rather than design.

## 4.2. Development

This section presents the development and features of each single tool grouped into the three categories presented above.

### 4.2.1. Information tools

#### 4.2.1.1. Internal insulation guide

The “Internal insulation guide” integrated into the FuturHist toolkit is based on the outcomes and knowledge generated within the RIBuild research project (RIBuild, 2020). Rather than reproducing the complete RIBuild knowledge base, the guide was developed as a concise and practitioner-oriented navigation tool that translates the extensive online RIBuild resources into a structured decision-making workflow for architects, consultants and other professionals involved in the retrofit of historic buildings. The full guide is included in Annex 12.1 of this deliverable.

The motivation for including the guide in the FuturHist toolkit was the recognition that internal insulation remains one of the most challenging retrofit measures in historic buildings. While it can significantly improve energy performance, it also introduces risks related to moisture accumulation, condensation, freeze-thaw deterioration, mould growth and compatibility with

heritage fabric. The RIBuild project produced a comprehensive body of knowledge, guidance documents, databases and calculation tools to address these issues. However, the breadth of available information can be difficult to navigate for non-specialist users. The FuturHist guide therefore acts as an entry point that structures the decision-making process and directs users to the most relevant RIBuild resources when more detailed information is required.

The guide was developed around a seven-step workflow that follows the progression of an internal insulation project (Figure 10). This format was tested previously with the Heat Pump guide (see section 4.2.1.4.)

INTERNAL INSULATION IN HISTORIC BUILDINGS

## Overview: planning internal insulation with RIBuild

Use the seven steps below as a quick route through the RIBuild material. Each step points to the corresponding RIBuild subsection so the full technical content remains one click away.

|                                                                                       |                                                                                          |                                                                                                |
|---------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| <b>1 Define what you want</b><br>Set goals and priorities before comparing solutions. | <b>2 Check what you have</b><br>Screen the building and identify warning signs.          | <b>3 Understand risks and constraints</b><br>Map exposure, sensitive parts and indoor climate. |
| <b>4 Collect evidence</b><br>Use measurements and checklists where needed.            | <b>5 Identify insulation options</b><br>Compare system families and application methods. | <b>6 Test performance</b><br>Use RIBuild tools to review hygrothermal and energy outputs.      |
| <b>7 Evaluate and decide</b><br>Compare energy, LCA/LCC and final project priorities. | <b>Tip</b><br>Follow the links in each step for the detailed RIBuild subsection.         |                                                                                                |

Direct links: [Set your Goal](#) | [Know your building](#) | [Insulation Systems](#) | [LCA/LCC](#)

Figure 10. Overview of the process as presented in the “Internal insulation guide”.

The process begins with the definition of project goals and priorities, followed by an initial assessment of the building condition and the identification of potential risks and constraints. Subsequent steps support the collection of evidence through inspections and measurements, the identification of suitable insulation systems, the evaluation of their performance and, finally, the comparison of alternatives against the original project objectives. Throughout the workflow, users are guided towards the corresponding sections of the RIBuild knowledge base through direct hyperlinks, ensuring that detailed explanations, checklists, and technical background information remain accessible.

Rather than asking users to select insulation products immediately, it encourages them to first establish retrofit objectives, assess building conditions and understand moisture-related risks before considering technical solutions. The guide explicitly highlights that the process is iterative and that information discovered during later stages may require revisiting earlier decisions. This approach is consistent with the whole-building philosophy adopted within both RIBuild and FuturHist and helps reduce the risk of inappropriate retrofit interventions.

To improve usability, the guide combines concise explanatory text with visual diagrams, decision workflows, illustrations and summary tables. Emphasis is placed on practical outcomes at the end of each step, enabling users to understand what information should be available before moving to the next stage. Examples include the documentation of project goals, identification of moisture-related defects, assessment of hygrothermal risks, selection of insulation system families and evaluation of energy, environmental and life-cycle cost performance.

On the one hand, the guide helps users understand the technical background required to answer the questions posed during the user-filtering stage of the toolkit (chapter 2). For example, users may be asked to identify signs of moisture damage, assess the presence of rising damp, describe ventilation conditions, or evaluate constraints related to the building fabric. The corresponding sections of the guide explain why this information is important, how it can be collected, and which risks it may indicate. On the other hand, when the decision trees identify internal insulation as a potentially suitable solution, users are directed towards the guide to obtain additional technical background before proceeding further. In this way, the guide supports informed decision-making rather than simply presenting a list of recommended solutions.

The final guide provides a compact, accessible and visually structured route through the RIBuild knowledge base while maintaining direct access to the underlying research, tools and technical documentation. In this way, FuturHist benefits from the scientific evidence generated by RIBuild while adapting its presentation and workflow to the needs of early-stage retrofit decision making in historic buildings.

### 4.2.1.2. Component integration guide

The component integration guide was developed within FuturHist to address a topic that is frequently overlooked in early-stage retrofit planning: the interaction between individual energy retrofit measures and the existing building envelope. While the performance of a retrofit measure is often evaluated at the level of individual components, its real-world performance depends heavily on how it is integrated into the surrounding construction. Junctions, interfaces and transitions between building elements can become critical points for heat loss, moisture accumulation, air leakage and material degradation. The guide therefore aims to support architects, consultants and retrofit practitioners in understanding and managing these interactions before detailed design work begins. The full guide is included in Annex 12.2 of this deliverable.

The guide was developed on the basis of the knowledge generated in Work Package 2 ‘Passive solutions for energy efficient historic buildings’ and presented in deliverable D2.8 ‘Insulation systems for the envelope’s retrofit including components’ integration’, which investigates the integration of insulation systems in historic buildings and analyses the influence of thermal bridges, airtightness, driving rain, rising damp and moisture-related risks on retrofit performance. Similarly to the approach chosen for the “Internal insulation guide”, rather than reproducing the detailed technical content of the deliverable, the guide translates its main findings into a concise and practice-oriented workflow that can be applied by users at the early

stages of project development. Its function is therefore similar to that of the internal insulation guide derived from RIBuild: to bridge the gap between scientific knowledge and practical decision-making, providing users with a structured route through a complex technical subject.

The guide is again organized around a seven-step workflow that mirrors the progressive logic of component integration during retrofit projects (Figure 11). The process begins with characterizing the building and understanding its construction, exposure conditions and moisture vulnerabilities. Particular emphasis is then placed on a dedicated risk-assessment stage, where users are encouraged to evaluate five key risk categories identified in FuturHist research: thermal bridges, airtightness, driving rain, rising damp and internal wall insulation prerequisites. Once these risks have been identified, the workflow continues with the mapping of vulnerable junctions, the selection of compatible measures, the development of construction details, performance verification and finally the documentation of decisions and residual risks. The guide explicitly highlights the iterative nature of the process and encourages users to revisit previous steps whenever new information reveals unacceptable technical risks.

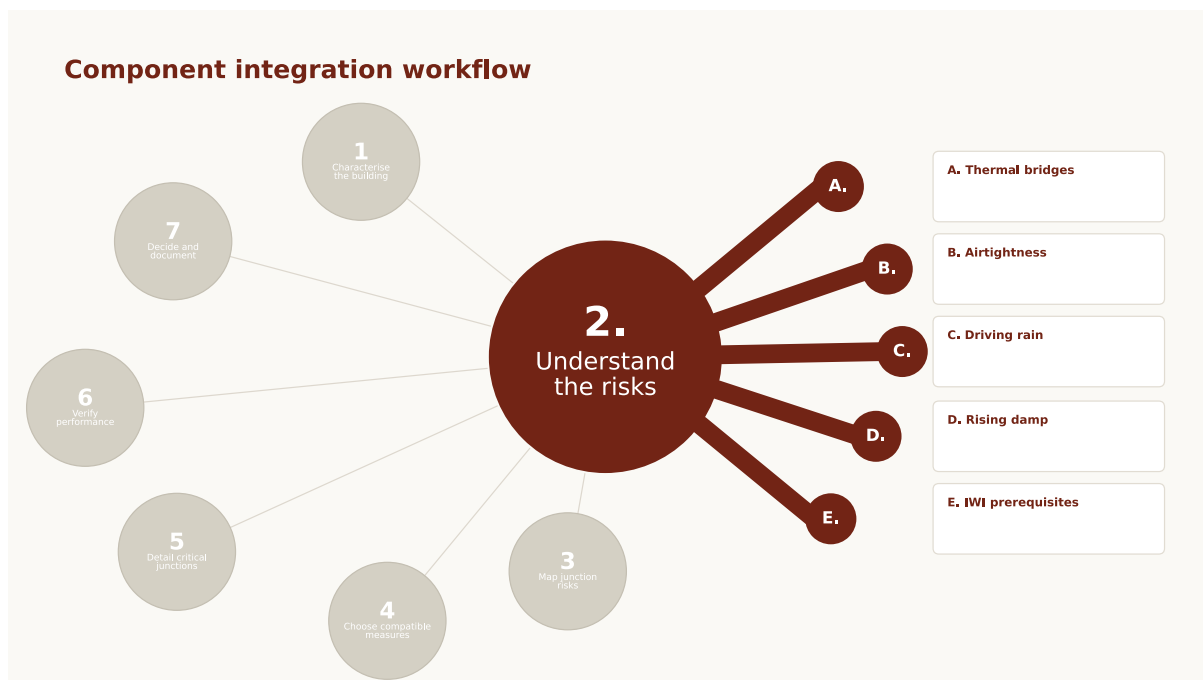


Figure 11. Component integration workflow as presented in the guide (see Annex 12.2).

A distinctive feature of the guide is its adoption of a component-integration perspective rather than a product-selection perspective. Instead of focusing on the performance of individual insulation materials, windows or building services, it addresses the physical mechanisms that determine whether a proposed intervention will perform successfully once integrated into the historic building envelope. Particular attention is therefore given to junctions such as wall-floor connections, wall-roof interfaces, window reveals, external wall-internal wall connections and plinth details, which often control thermal bridge losses, moisture accumulation and mould risks. The guide uses practical examples, illustrative diagrams and simplified performance indicators such as  $\psi$ -values and fRsi to explain how these issues can be identified and managed.

Beyond its role as a standalone guidance document, the component integration guide also supports the technical compatibility workflow implemented in the FuturHist toolkit. The guide informed the development of several technical-compatibility questions included in the decision-tree logic described in Chapter 2.1. Sections related to moisture diagnosis, rain exposure, airtightness continuity, thermal bridge risks and internal insulation prerequisites are used to identify the building characteristics and constraints that should be assessed during the user-filtering phase. As a result, the guide contributes indirectly to the filtering of solutions by helping define the information required to evaluate their technical feasibility.

The relationship between the guide and the decision trees follows the same logic described for the internal insulation guide. During the user-filtering stage of the toolkit, users are asked questions concerning building conditions, moisture sources, rain exposure, thermal bridge risks, airtightness strategies and the presence of sensitive junctions. The guide provides the technical background necessary to understand these questions and, where necessary, explains how the relevant information can be gathered. Conversely, once the filtering process has identified a set of technically compatible solutions, the user is directed towards the guide to better understand the implications of integrating those solutions into the building envelope. This interaction reflects the overall architecture illustrated in Figure 1. Simplified diagram of the hierarchical logic of the decision tree: inputs from other tools (orange shades), additional typology-based information (yellow), inputs from the user (light green), lists of filtered and selected solutions (dark green), where informing tools, decision-support tools and detailing tools are connected through the technical compatibility pathway. Users can therefore move from solution filtering to technical learning and subsequently to more detailed validation tools such as hygrothermal assessment or thermal-bridge evaluation.

To maximize usability, the guide combines concise explanatory text with summary tables, visual workflows, practical checklists and illustrative junction examples. Each step concludes with a clearly defined outcome that describes the information that should be available before proceeding further. This structure allows users with different levels of expertise to progressively build an understanding of the technical challenges associated with component integration while maintaining a clear connection to the more detailed technical resources developed in FuturHist.

#### 4.2.1.3. Photovoltaics guide

The photovoltaic (PV) integration guide was developed as a result of the work carried out in Work Package 3 “Active systems for a clean energy transition”, documented in deliverable D3.2 ‘Guidelines for RES integration’ (DOI [10.5281/zenodo.21379535](https://doi.org/10.5281/zenodo.21379535)) and published as part of the project outcomes (visit available resources in FuturHist website [www.futurhist.eu](http://www.futurhist.eu)). The guide supports architects, consultants and building owners in evaluating the suitability of photovoltaic systems for historic buildings while considering heritage significance, technical feasibility and energy performance objectives. As the guide has already been published as a standalone dissemination resource, it is not reproduced in full within this deliverable and can be accessed

through the FuturHist project website ([link](#)) as well as stable repositories like Zenodo and FuturHist Knowledge HUB.

The photovoltaic guide is classified as an informing tool. Its purpose is to provide users with the technical background required to understand the opportunities and constraints associated with photovoltaic integration before engaging in more detailed design activities. The guide presents key considerations related to roof suitability, visibility, heritage constraints, available solar exposure, installation options and integration strategies. Particular attention is devoted to balancing renewable energy generation with the preservation of the architectural and cultural values of historic buildings. The guide complements the solution-filtering process implemented through the decision trees by helping users understand the implications of photovoltaic systems once these have been identified as potentially suitable retrofit options.

The development process, technical contents and validation activities associated with the guide are described in detail in deliverable D3.2 'Guidelines for RES integration'. Within the context of technical compatibility, the guide contributes to increasing user awareness of the main design constraints and decision criteria associated with the integration of renewable energy systems in historic buildings.

### 4.2.1.4. Heat pump guide

The heat pump guide was also developed within Work Package 3 and its contents published as part of deliverable D3.2 'Guidelines for RES integration'. The guide provides practical support for evaluating the applicability of heat pump systems in historic buildings and explains the principal technical conditions that influence their successful integration. Similar to the photovoltaic guide, it was published as an independent resource and is therefore referenced rather than reproduced within this deliverable ([link](#)).

Within the FuturHist technical compatibility framework, the heat pump guide also belongs to the category of informing tools. Its objective is to familiarize users with the key concepts that determine heat pump feasibility and performance, including heat demand reduction, supply temperature requirements, compatibility with existing heat emission systems, available technical space, noise considerations and electricity supply requirements. The guide follows the same practitioner-oriented and step-by-step structure adopted in the other FuturHist guidance documents, translating technical knowledge into an accessible format that can be used during early retrofit planning.

The guide is complemented within the toolkit by additional decision-support checks developed specifically for active systems and described in Chapter 4.2.2.3. Together, the guide and the associated feasibility checks provide a progressive pathway from general understanding to preliminary technical assessment. Detailed information on the development, testing and contents of the guide is reported in deliverable D3.2.

## 4.2.2. Decision-support tools

The informational resources described in the previous section are complemented by a series of decision-support tools that provide qualitative and quantitative assessments of technical compatibility. While the guides are intended to improve users' understanding of retrofit opportunities and constraints, the tools presented in this section support the comparison, prioritisation and validation of alternative solutions based on building-specific technical criteria.

### 4.2.2.1. Hygrothermal validation of Internal insulation

As mentioned previously, the RIBuild project developed an online insulation calculation tool ([link](#)) (RIBuild, 2020), which allows users to evaluate the hygrothermal compatibility of internal insulation systems for historic masonry buildings through a large database of pre-calculated simulations. The RIBuild tool is based on transient hygrothermal simulations for solid brick and stone masonry walls combined with different insulation systems and climatic conditions representative of seven European countries: Belgium, Denmark, Germany, Italy, Latvia, Sweden and Switzerland. The results are made available through a simple user interface that allows practitioners to identify potentially suitable internal insulation solutions without carrying out project-specific numerical simulations.

Although the RIBuild tool represents a valuable resource for early-stage decision making, the wall typologies, climatic conditions and insulation systems included in the original database do not fully cover the historic building stock addressed by FuturHist. For this reason, the tool was expanded within Work Package 2 to include additional wall assemblies, insulation materials and climatic locations representative of the FuturHist typologies. Furthermore, the simulation matrix was extended to include future climate scenarios, allowing users to assess not only the current hygrothermal compatibility of internal insulation systems but also their robustness under changing climatic conditions. This is particularly relevant for historic buildings, where increasing temperatures, changing precipitation patterns and evolving moisture loads may significantly affect the long-term performance and durability of retrofit interventions. The development of the extended database and the associated validation work are described in detail in deliverable D2.8 'Insulation systems for the envelope's retrofit including components' integration' ([link](#)), particularly in Chapter 2.

Rather than requiring users to perform complex numerical simulations, the results of thousands of pre-calculated scenarios are made available through a simplified interface (Figure 4), allowing users to explore the influence of wall type, insulation material, climate, rain exposure and indoor moisture load on hygrothermal performance. Results are presented in a simplified way with a traffic light system indicating those that are clearly moisture safe but leaving the possibility to still select those cases with more uncertain results (or not yet calculated) in case further and more detailed analysis can be carried out by the user.

Furthermore, and in contrast to many hygrothermal assessment approaches that provide several temperature- and moisture-related outputs, FuturHist deliberately focuses on a single performance indicator: mould risk, expressed through the mould growth index. This choice was made to improve the interpretability of results for non-specialist users and to ensure consistency with the technical compatibility KPI framework developed within the project, where mould risk was selected as the principal indicator for assessing moisture-related technical compatibility. While mould growth is the indicator presented to users, it also acts as a proxy for a wider range of moisture-related deterioration mechanisms within building components.

Consistent with the original RIBuild methodology, the simulations were performed using the DELPHIN software (Bauklimatik Dresden, 2026), a transient heat and moisture transfer model widely used for the assessment of historic building envelopes. In addition, FuturHist introduced a comparison between DELPHIN and WUFI simulations (Fraunhofer IBP, 2026) to evaluate the consistency of results obtained with two of the most used hygrothermal simulation tools. This comparison, documented in deliverable D2.8 'Insulation systems for the envelope's retrofit including components' integration', provides additional transparency regarding modelling assumptions and offers useful information for advanced users interested in more detailed hygrothermal analyses.

The resulting database constitutes one of the principal decision-support resources within the technical compatibility dimension of the FuturHist toolkit. It provides quantitative evidence regarding the moisture-related risks associated with internal insulation systems. The tool therefore supports the comparison and prioritization of alternative solutions by identifying configurations that are likely to be hygrothermally safe and highlighting situations where further investigation or project-specific simulations may be required. Rather than being developed as a standalone application, the simulation results are integrated directly into the FuturHist toolkit and made available through the technical compatibility assessment workflow. This approach allows users to move seamlessly from solution filtering to quantitative validation without leaving the toolkit environment. Furthermore, FuturHist does not view the current database as a fixed outcome, but rather as the foundation for a growing knowledge base. As the toolkit evolves, the ambition is to progressively integrate both the original RIBuild simulation data and additional datasets covering new building typologies, climates and retrofit solutions beyond those specifically developed within FuturHist. In this way, the technical compatibility module can continue expanding over time and progressively increase its relevance and applicability across the wider European historic building stock.

#### 4.2.2.2. Component integration in typologies

The "Component integration in typologies" tool was developed as a decision-support resource to help users assess whether specific junction solutions are compatible with the selected building typology and retrofit solution. It builds on the technical content presented in the component integration guide described in Chapter 4.2.1.2, but it is positioned at a later stage of the workflow. While the guide supports users in understanding the main risks associated with component

integration, this tool becomes relevant after one or more retrofit solutions have been selected, when the user needs to identify the junctions that may require further attention and understand which construction details are potentially compatible with the specific building typology.

As described in section 4.2.1.2, retrofit measures cannot be assessed only at the level of individual components as junctions often determine their feasibility. The tool translates the typology-based assessment developed in Chapter 4.2 of Deliverable 2.8 – “Insulation systems for the envelope’s retrofit including components’ integration” into an operational format for the toolkit. The core of the tool is the compatibility matrix presented as Table 43 in that report (see Figure 12), which was developed by combining the component integration strategies and junction solutions identified within the project with the characteristics and constraints of the FuturHist building typologies defined in deliverable D1.2 ‘Building typology: analysis of the building stock and typologies definition’. For each typology, the proposed solutions were assessed considering heritage constraints, construction characteristics and potential technical risks associated with their implementation. The resulting matrix provides a systematic overview of the applicability of different component integration measures across the various typologies. Rather than providing a detailed design recommendation, the matrix serves as a screening mechanism that highlights which solutions are potentially compatible, which may require additional information or assessment, and which are unlikely to be suitable within a given building context.

Table 43. Assessment of measures and solutions for proper design of the building envelope, including junctions and integration of components, for each typology. “not required” (X), “not compatible” (XX), “compatible but not implemented” (✓), “implemented in the DC” (✓✓), “information missing” (?).

| Topic               | Solution                  | ES 1* | ES 2 | PL 1* | PL 2 | SE 1* | SE 2 | SC 1* | SC 2* | SC 3 |
|---------------------|---------------------------|-------|------|-------|------|-------|------|-------|-------|------|
| Energy losses/mould | Insulation wedge          | ✓     | ✓    | ✓     | ✓    | ✓     | X    | ✓     | ✓     | ✓    |
| Mould/moisture      | Heat-conducting plate     | ?     | ?    | ✓     | ✓    | ?     | ?    | ✓     | ✓     | ✓    |
| Airtight layer      | Internal plaster          | ✓✓    | ✓    | ✓✓    | ✓    | ✓✓    | ✓    | ✓✓    | ✓     | ✓    |
| Airtight layer      | Concrete layer            | XX    | XX   | XX    | ✓    | XX    | ✓    | XX    | XX    | XX   |
| Airtight layer      | Air thigh membrane        | ✓     | ✓    | ✓     | ✓    | ✓     | ✓    | ✓     | ✓     | ✓    |
| Airtight layer      | Taped or glued panels     | ✓     | ✓    | ✓✓    | ✓    | ✓     | ✓    | ✓     | ✓     | ✓    |
| Airtight junctions  | Adhesive tape             | ✓     | ✓    | ✓✓    | ✓    | ✓✓    | ✓    | ✓     | ✓     | ✓    |
| Airtight junctions  | Joint sealing             | ✓✓    | ✓    | ✓✓    | ✓    | ✓✓    | ✓    | ✓     | ✓     | ✓    |
| Airtight junctions  | Lip seal                  | ✓     | ✓    | ✓✓    | ✓    | ✓✓    | ✓    | ✓     | ✓     | ✓    |
| Rain protection     | External plaster          | ✓     | ✓    | ✓✓    | ✓    | ✓✓    | ✓    | ✓✓    | XX    | XX   |
| Rain protection     | Rainscreen cladding       | XX    | XX   | XX    | ✓    | XX    | XX   | ✓     | XX    | XX   |
| Rain protection     | Hydrophobic treatment     | X     | X    | ✓     | ✓    | ?     | ?    | ✓     | XX    | XX   |
| Rain protection     | Roof overhangs            | XX    | XX   | XX    | ✓    | ✓✓    | ✓    | XX    | XX    | XX   |
| Rain protection     | Doors/windows pulled back | X     | X    | XX    | XX   | ?     | ?    | XX    | XX    | XX   |
| Rain protection     | Dimpled membrane          | ✓     | ✓    | ✓     | ✓    | X     | ✓    | XX    | XX    | XX   |
| Rain protection     | Profile with drip edge    | ✓     | ✓    | ✓     | ✓    | ✓     | ✓    | XX    | XX    | XX   |
| Rising damp         | Runoff stream             | ✓✓    | ✓    | ✓     | ✓    | ✓✓    | ?    | XX    | ✓     | ✓    |
| Rising damp         | Paraffin injection        | ?     | ?    | ✓     | ✓    | X     | X    | XX    | XX    | XX   |
| Rising damp         | Moisture barrier          | ✓     | ✓    | ✓     | ✓    | XX    | XX   | XX    | XX    | XX   |

\*Typology with demo case.

Figure 12. Junction solution assessment matrix as reported in deliverable D2.8 ‘Insulation systems for the envelope’s retrofit including components’ integration’. The eight columns to the right show the results for the FuturHist typologies.

In the toolkit workflow, the component integration in typologies tool is activated after the user has selected a retrofit solution from the filtered list of potentially compatible measures. At this point, the toolkit can generate a warning indicating that the selected solution may affect specific junctions or interfaces within the building envelope. The warning does not exclude the solution

automatically but alerts the user that successful implementation depends on appropriate detailing. The user is then directed to the component integration in typologies tool, where the relevant typology and retrofit solution is used to identify the junctions that should be considered and to explore potentially compatible integration strategies.

The tool therefore acts as a bridge between the early filtering of retrofit solutions and the subsequent detailing tools. Its input is the typology selected through the typology finder together with the retrofit solution selected by the user. Its output is a typology-specific indication of relevant junctions, associated risks and potentially compatible integration approaches. These outputs are qualitative rather than predictive and are intended to support early-stage decision-making by drawing attention to the technical implications of a selected solution before the project advances towards detailed design or numerical validation. Within the overall technical compatibility framework, the tool helps ensure that solution selection is complemented by an early consideration of the junctions and interfaces that ultimately determine the performance and durability of retrofit interventions in historic buildings.

#### 4.2.2.3. Technical requirements for active systems

This section reports three checks that are meant to guide the toolkit user about some specific aspects in relation to the possible implementation of a heat pump system. These checks should be considered an addition to the indications reported in the heat pump guide for the air-water heat pump systems and help in deciding whether an air-water heat pump system is a feasible solution or not for the case considered.

All three checks are structured with a maximum of two questions and, depending on the input from the user, the result could be an indication that the configuration considered does not present problems, or a warning. In none of the cases, these three checks lead to excluding solutions from the long list.

The first check applies to all heat pumps using water as heat carrier fluid and regards the supply water temperature level that is going to be used (or that is planned to be used) at the heat emission system. As heat pump systems are, in general, more efficient (i.e., present a higher COP) when a low supply water temperature is used; first a check is done to verify whether the supply water temperature is managed in a variable or fixed way. If it is controlled in a variable way, it is considered that the temperature is set to use the minimum supply water temperature that ensures the covering of the building thermal demand. If instead the supply water temperature is managed in a fixed way, a further question is posed to the user to identify whether the fixed temperature level is below or above a certain threshold. This threshold is set to 55 °C as this is the temperature level that is generally reached by most of the machines available on the market. Supply water temperatures above this threshold should be verified and cannot be considered a common characteristic of many of the machines.

As a result of the check, if the supply water temperature is managed with a fixed set point higher than 55 °C, a warning appears to the user, informing about the limited system efficiency in this

condition, about the possibility for some machines to not reach the set point water temperature, and suggesting a possible alternative (an hybrid system composed by an air-water heat pump system and a gas boiler) which, in this case, could be a solution worth considering. Figure 13 shows the logic of this check.

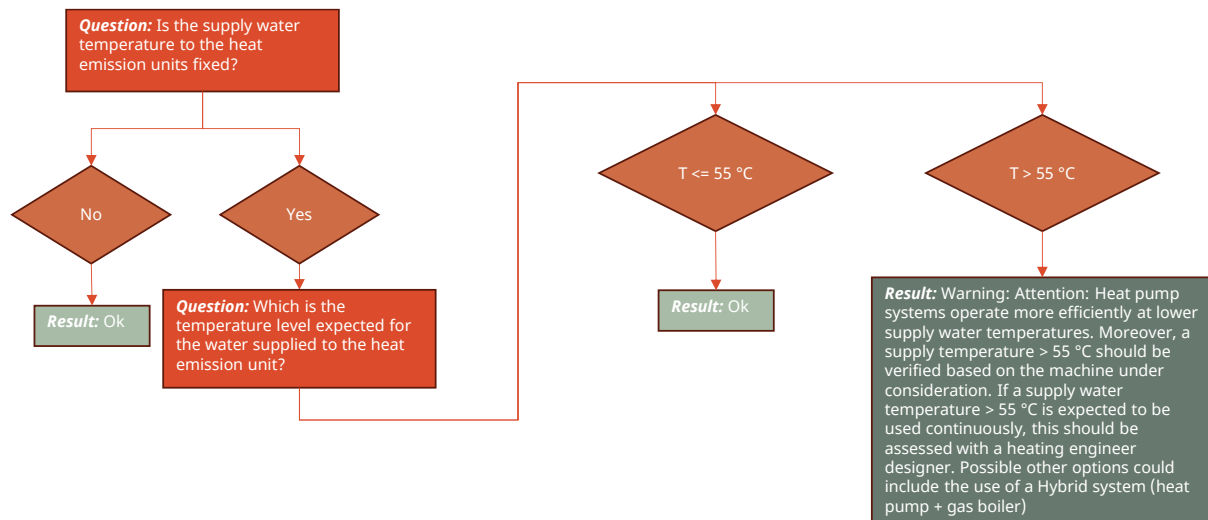


Figure 13. Logic to check the supply water temperature level used in the case an air-water heat pump system is considered.

The second check applies to all heat pump systems and regards the electric power connection of the building. In fact, the available electric power connection already available in the building, or that can be requested from the local Distributor System Operator (DSO), can be, in some cases, limited. Although this limitation is not frequent, it is worth considering as, if an adequate electric power connection cannot be obtained in the considered building, this prevents the installation of a heat pump system. As a general indication, the electric power connection needed for a heat pump system can be considered, for most cases, in the range of 40-65 % of the thermal power in nominal conditions of the heat pump considered. This range is obtained by analyzing a series of datasheets of air-water heat pump systems available on the market having a thermal power in nominal conditions in the range 5-100 kW. This aspect of the electric power connection is quite technical and should be managed with a heating engineer designer and, eventually, in collaboration with the DSO. Figure 14 shows the logic of this check on the building's electric power connection.

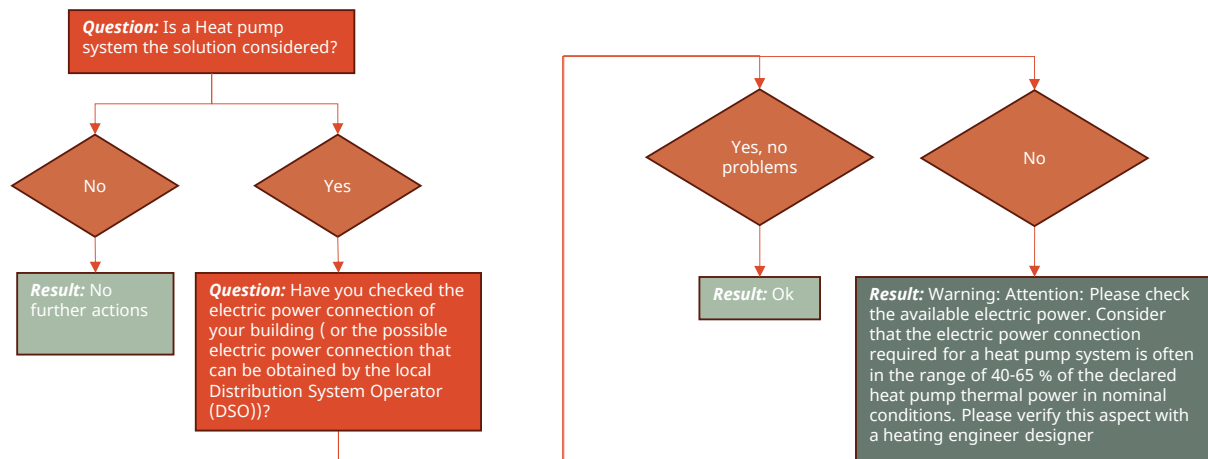


Figure 14. Logic to check the building's electric power connection if a heat pump system is considered.

The third check applies only to air-water heat pump systems, as it aims to warn the user about the need to have a technical space where to install the outdoor unit of the system and give a general indication about the footprint area necessary for this installation. The numeric indications given about the footprint area are a function of the thermal power in nominal conditions of the considered system. These indications are calculated, as for the first check reported above, analysing the same technical datasheet, hence can be considered valid for machines with a thermal power in nominal conditions in the range 5-100 kW, a range that includes most air-water heat pump applications. Figure 15 shows the logic of this check.

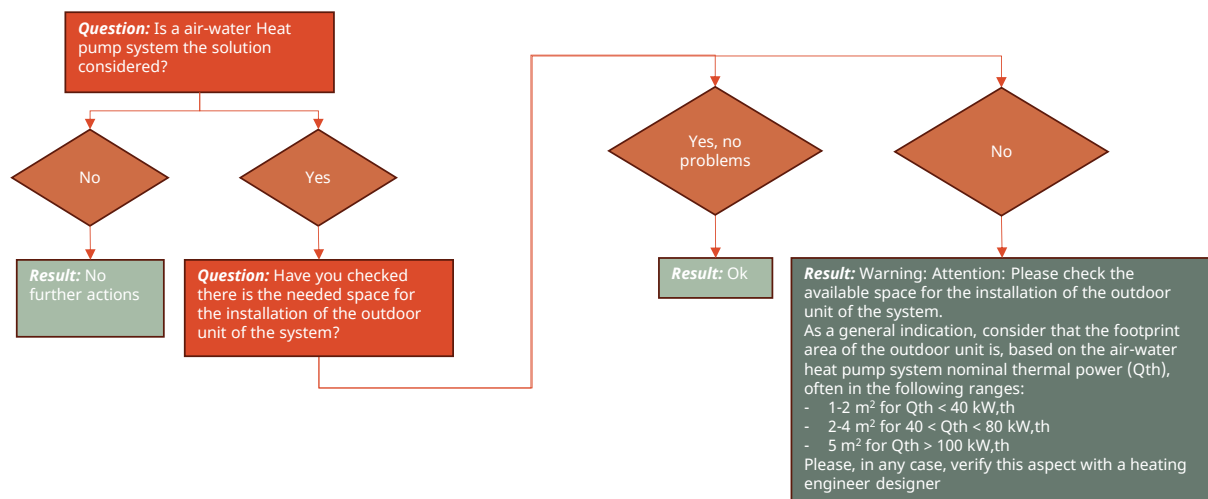


Figure 15. Logic to check the footprint area needed for the outdoor unit if an air-water heat pump system is considered.

### 4.2.3. Detailing tools

The tools presented in this section provide more detailed analyses, measurements and implementation examples that can support the transition from solution selection to project-specific design and verification activities.

#### 4.2.3.1. Validation of thermal bridges

The validation of thermal bridges represents the final stage of the component integration workflow established within FuturHist. Following the component integration guide (Chapter 4.2.1.2), which introduces the main integration risks and principles, and the component integration in typologies tool (Chapter 4.2.2.2), which identifies the junctions and integration strategies relevant for a given building typology, this tool provides examples of practical detailing solutions that can support the implementation of retrofit measures in historic buildings.

The tool is based on the detailing examples presented in Chapter 4.3 of deliverable D2.8 'Insulation systems for the envelope's retrofit including components' integration'. These examples were developed to illustrate how common component integration challenges can be addressed at critical junctions and interfaces within the building envelope of the studied typologies. The proposed details aim to reduce the risks associated with thermal bridges, moisture accumulation, air leakage and material incompatibility while respecting the constraints typical of historic buildings. The details therefore serve as illustrative examples of good practice rather than prescriptive design solutions.

Within the FuturHist toolkit, access to the examples of validated thermal bridges is triggered after a retrofit solution has been selected and the relevant junctions have been identified through the component integration in typologies tool. Users are directed towards detailing examples that correspond to the selected solution and the typology-specific integration challenges previously identified (Figure 16). In this way, the workflow progressively guides users from understanding the risks, to identifying relevant junctions, and finally to exploring possible implementation approaches.

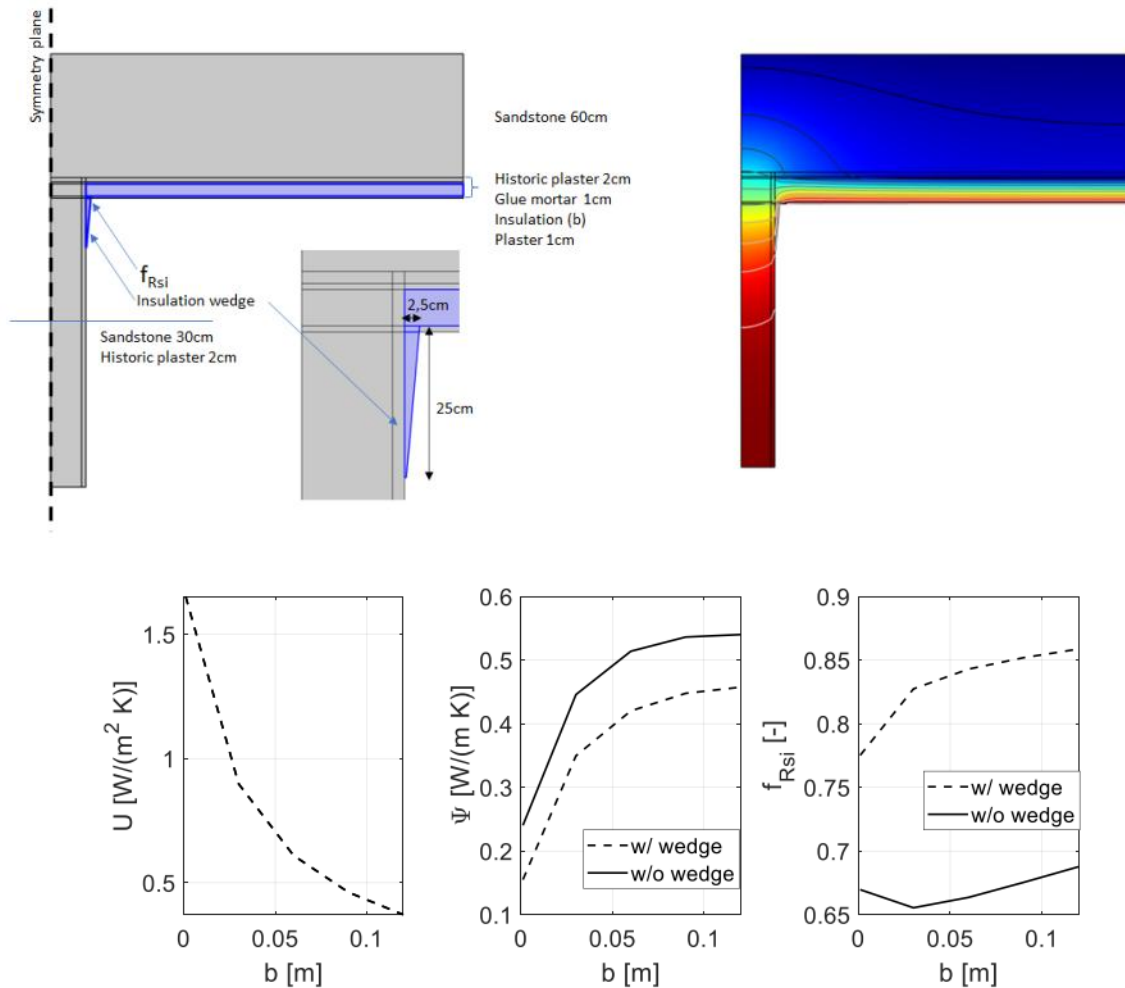


Figure 16. Example of junction solution details from deliverable D2.8 'Insulation systems for the envelope's retrofit including components' integration'.

It is important to note that the detailing examples included in the tool are not exhaustive and do not cover all possible combinations of building typologies, construction systems and retrofit solutions. The examples were developed for the project typologies and are representative of situations encountered within the project. They should therefore be considered as reference cases rather than complete design guidance. In many practical applications, project-specific adaptations will be necessary to account for the characteristics of the building, heritage requirements, structural conditions and local regulations.

Consequently, the detailing tool is intended to support and inform early design decisions rather than replace professional design activities. While some users may be able to adapt the examples directly to their projects, others may require additional analyses or the support of specialised consultants to develop suitable junction details. The tool nevertheless provides a valuable starting point by illustrating the principles that should be considered when translating selected retrofit solutions into technically compatible and robust construction details.

#### 4.2.3.2. Heat flux calculator

The heat flux measurement analysis tool (HeatFlux Tool) was developed within FuturHist to support the interpretation of in-situ thermal performance measurements carried out on building components. The tool was originally created to analyse the extensive monitoring campaign performed in the Grigno test cells as part of the experimental activities reported in deliverable D2.4 'Self-healing external finishing'. The measurements collected during these experiments generated large datasets of heat flux, surface temperature and air temperature values, highlighting the need for a dedicated tool capable of processing and interpreting the data in a consistent and transparent manner.

The tool implements the average method described in ISO 9869-1:2014, the internationally recognised standard for the in-situ determination of thermal resistance and thermal transmittance of building elements (International Organization for Standardization (ISO), 2014). The method uses measured heat fluxes together with internal and external temperature differences over a sufficiently long monitoring period to estimate the thermal performance of the analysed construction. By automating the data processing workflow and the calculation procedures defined by the standard, the tool reduces the effort required to analyse monitoring campaigns and provides a consistent framework for evaluating measured thermal performance.

Although initially developed to support research activities within FuturHist, the tool can also be valuable for advanced users carrying out on-site investigations of existing buildings. In particular, it complements the workflow presented in the internal insulation step-by-step guide, where in-situ measurements are identified as a valuable source of information when assessing the characteristics and performance of existing walls before selecting retrofit solutions. Measured thermal properties can help reduce uncertainties regarding the existing construction and provide additional evidence to support retrofit decisions, especially in situations where the composition of the wall is unknown or differs from standard assumptions.

Within the FuturHist toolkit, the heat flux measurement analysis tool is positioned at the most advanced level of the technical compatibility workflow. Unlike the informing guides and pre-calculated decision-support resources described in previous sections, its use requires users to collect monitoring data directly on site using heat flux sensors and temperature measurements. Consequently, it is not expected to be used by all toolkit users, but rather by practitioners seeking a higher level of confidence in the characterisation of existing constructions or in the validation of retrofit interventions. The tool therefore supports situations where simplified assumptions or typology-based assessments are insufficient and where direct measurements can provide project-specific evidence.

The heat flux measurement analysis tool should be viewed as a complementary resource that strengthens the overall evidence-based approach of the FuturHist toolkit. Users can initially rely on the guides, decision trees and compatibility assessments to identify and screen suitable retrofit solutions, while the heat flux tool offers the possibility of undertaking more detailed investigations when required. In this way, the toolkit provides a progressive pathway from

qualitative assessment and typology-based guidance towards increasingly detailed and project-specific technical validation.

The tool can be openly accessed from the GitHub repository ([link](#)). An example of results calculated and visualized with the HeatFlux tool is shown as Figure 17.

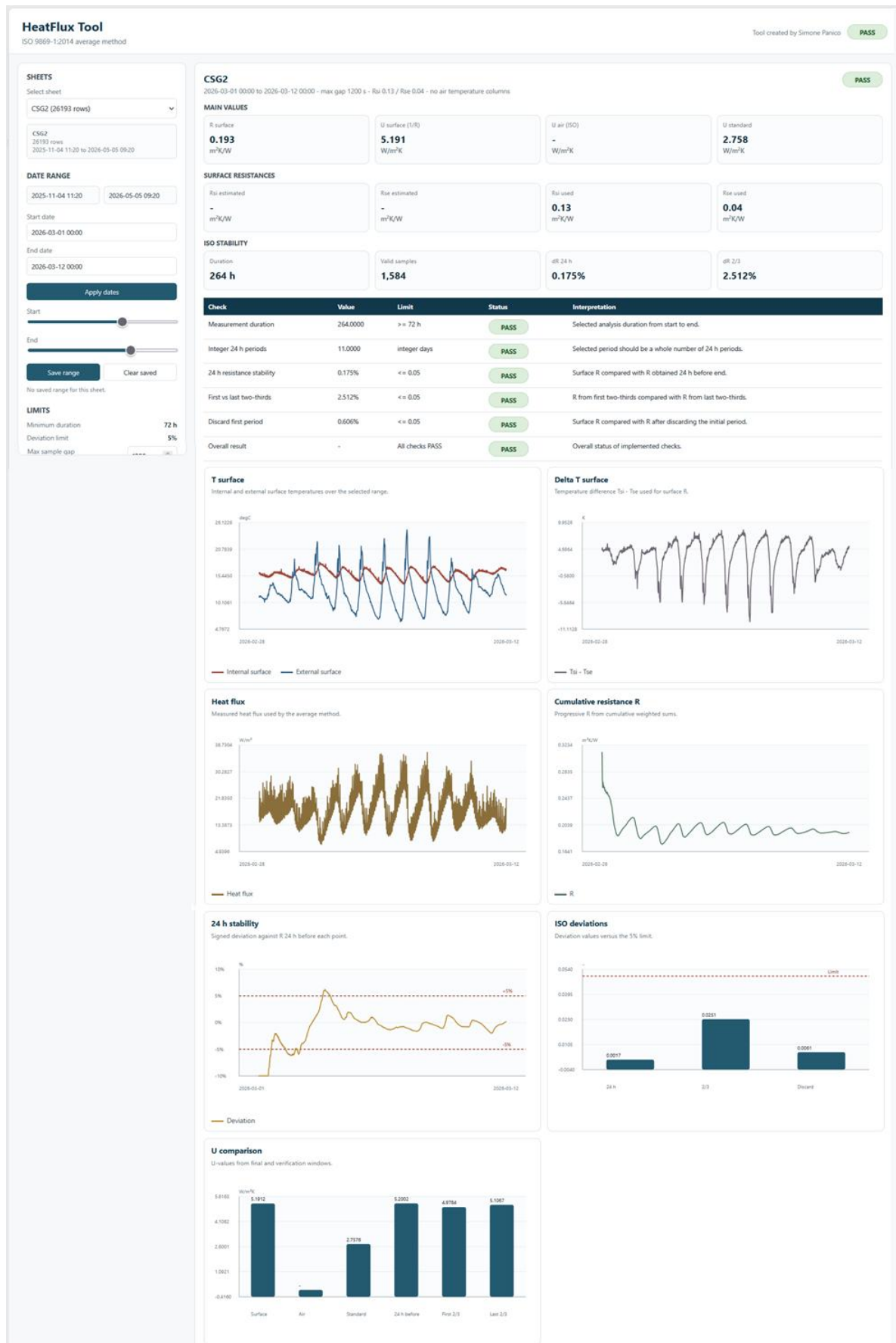


Figure 17. Example of R- and U-value results calculated and visualized with the HeatFlux tool.

## 4.3. Testing

The technical compatibility dimension includes a diverse set of resources ranging from educational guides and typology-based decision-support tools to numerical simulations and advanced validation tools. As a consequence, no single testing methodology was applicable to all resources. Instead, the validation approach was adapted to the nature and maturity of each resource, distinguishing between: (i) informing tools, whose primary purpose is knowledge transfer; (ii) decision-support tools, which assist users in assessing the technical feasibility of retrofit solutions; and (iii) detailing tools intended for more advanced technical validation and design support.

### 4.3.1. Information tools

The internal insulation guide, component integration guide, photovoltaic guide and heat pump guide were not validated through numerical testing, as their primary purpose is to communicate and structure existing knowledge rather than generate new calculations. Validation therefore focused on ensuring that the content was correctly translated into a practitioner-oriented format and remained consistent with the underlying scientific and technical sources.

For the internal insulation guide, the primary validation consisted of reviewing the translation of knowledge from the RIBuild project into the adopted step-by-step format. The guide was reviewed by experts involved in the original RIBuild project to ensure that the proposed workflow, terminology and recommendations remained consistent with the source material. Similarly, the component integration guide was reviewed by the authors of the original research presented in deliverable D2.8 'Insulation systems for the envelope's retrofit including components' integration' to verify that the key findings related to component integration were accurately represented. The photovoltaic and heat pump guides had already undergone review and testing during their development within Work Package 3 and through their application in the FuturHist Retrofit Academy. No additional validation activities were therefore considered necessary within Task 4.2.

### 4.3.2. Decision-support tools

The validation of the decision-support tools depended on the origin of the information used and the intended role of the tool within the toolkit workflow.

The internal insulation hygrothermal validation tool builds directly on the simulation framework developed in the RIBuild project and extended within FuturHist. The associated simulation work included a comparison between DELPHIN and WUFI models to assess the consistency of results and identify potential modelling uncertainties. These activities are described in detail in deliverable D2.8 'Insulation systems for the envelope's retrofit including components' integration' and constitute the primary validation of the underlying simulation database. Since

the simulation results will not be presented to users through a standalone application, but rather integrated into the toolkit workflow as part of the technical compatibility assessment, future testing activities will focus primarily on usability and integration within the overall user experience.

The component integration in typologies tool is based on the compatibility matrix presented in deliverable D2.8 and developed through expert assessment of the FuturHist building typologies. The validation of this resource therefore relied primarily on expert review during its development. Given the qualitative and typology-based nature of the matrix, its practical usefulness can only be fully assessed through application to a wider range of buildings. Consequently, future testing within the toolkit will focus on evaluating whether users find the generated warnings and recommendations understandable, relevant and supportive for decision-making.

The technical requirements for active systems are based on established engineering principles and simplified feasibility checks concerning supply temperatures, electrical power availability and space requirements. Their role within the toolkit is informational rather than predictive, and their effectiveness therefore depends primarily on how clearly they communicate potential constraints to users. Testing activities will consequently focus on usability, clarity and integration within the decision-tree workflow rather than on verification of the underlying technical principles.

### 4.3.3. Detailing tools

The detailing tools represent the most advanced level of technical compatibility support and required a different validation strategy.

The component integration detailing tool is based on detailing examples developed in deliverable D2.8 'Insulation systems for the envelope's retrofit including components' integration'. Since these examples are intended as illustrative references rather than prescriptive design solutions, validation focused on ensuring consistency between the presented details, the corresponding typologies and the component integration workflow. The examples themselves are based on established principles of building physics and previous project work. Future improvements are expected to result primarily from user feedback and the expansion of the range of available examples rather than from further technical validation.

The heat flux measurement analysis tool constitutes the only technical compatibility resource developed as an independent computational tool. Validation was performed by comparing the results generated by the software with manual calculations performed according to ISO 9869-1:2014 using measurement data collected during the experimental campaigns carried out within Work Package 2 and presented in deliverable D2.4 'Self-healing external finishing' and D2.5 'Low thermal conductivity external finishing'. The comparison confirmed that the automated implementation reproduces the results obtained through manual application of the standard method while significantly simplifying the analysis process and the verification of convergence criteria.

### 4.3.4. Overall assessment

The testing activities confirmed that the technical compatibility resources are sufficiently mature for integration into the FuturHist toolkit. For most resources, the priority was not the validation of the underlying scientific content, which had already been developed and reviewed within previous projects or FuturHist deliverables, but rather the verification that this knowledge could be effectively translated into tools supporting the early-stage decision-making process targeted by the toolkit. The next phase of testing will therefore focus primarily on usability, user interaction and the integration of these resources into the overall toolkit workflow, as reported in the subsequent deliverables dedicated to toolkit implementation and user testing.

## 4.4. Results and discussion

The technical compatibility dimension developed within FuturHist provides a structured framework that supports users from the initial identification of technically compatible retrofit solutions to their validation and implementation. The resulting resources combine informing guides, decision-support tools and detailing resources, creating a progressive workflow that complements the overall decision-tree logic of the toolkit. Rather than focusing on a single assessment method, the dimension integrates knowledge transfer, typology-based assessments and quantitative validation tools to address the diverse technical challenges associated with the retrofit of historic buildings.

A major outcome of the work is the successful integration of results generated both within FuturHist and in previous research projects. The internal insulation resources build on the RIBuild project, while the component integration tools originate from the activities carried out in Work Package 2. Similarly, the photovoltaic and heat pump guides transfer the outcomes of Work Package 3 into resources that can be used during the early design stages. This approach avoids duplicating existing knowledge while ensuring that proven methods and evidence are presented in a format compatible with the FuturHist workflow.

One of the main challenges encountered during development was balancing scientific robustness with usability. Many of the underlying methods are based on advanced building-physics analyses that are difficult to apply during early-stage decision making. This challenge was addressed through simplified workflows, step-by-step guidance and the use of easily interpretable outputs, such as the adoption of mould-growth risk as the principal indicator for hygrothermal compatibility. The resources were also organised into different levels of complexity, allowing users to access additional information and validation tools only when needed. The choice of mould-growth risk as the primary indicator for hygrothermal validation is a clear example of this approach, allowing technically complex simulation results to be translated into an output that can be more easily interpreted by practitioners.

From the perspective of the FuturHist KPI framework, the technical compatibility resources contribute primarily to reducing the risks associated with retrofit interventions and supporting

the selection of technically feasible solutions. Particular attention was devoted to moisture-related risks, condensation, mould growth, thermal bridges, driving rain, rising damp and the integration of active systems within historic buildings. The resources therefore provide direct support to the technical compatibility objectives defined in deliverable D1.6 'Assessment categories and KPIs: a multidimensional approach to performance assessment' and help users identify situations where additional validation, monitoring or expert support may be required before implementation. While the Smart Readiness Indicator is also part of the broader technical compatibility framework established in the project, it is addressed separately in Chapter 9 due to its role as a scenario evaluation tool rather than a solution compatibility assessment.

Overall, the work demonstrates how technical compatibility can be incorporated into a decision-support toolkit through a combination of transferable knowledge, typology-based assessments and targeted validation resources. The resulting tools do not replace detailed design or specialist analyses, but they provide users with a structured pathway for identifying risks, understanding constraints and selecting more robust retrofit solutions at the early stages of project development. Future activities will focus primarily on further integration of these resources into the digital toolkit and on collecting user feedback to improve usability, expand the available datasets and refine the interaction between the different components of the technical compatibility workflow.

### KPI alignment

The technical compatibility resources described in this chapter are aligned with the assessment framework established in Deliverable D1.6 'Assessment categories and KPIs: a multidimensional approach to performance assessment'. Within that framework, Smart Readiness is the principal KPI under technical compatibility, while mould risk is included as a supporting indicator. Other aspects addressed by the resources, including thermal bridges, airtightness, driving rain, rising damp, structural and fire risks, constructability and the feasibility of active systems, are considered decision criteria that should inform the selection and development of retrofit scenarios. The Smart Readiness KPI is evaluated through the dedicated SRI tool described in Chapter 9 and is therefore not calculated by the tools presented in this chapter.

The tools included here are part of the decision-tree logic described in chapter 2 to identify suitable retrofit solutions and thus support the definition of retrofit scenarios that are later evaluated in terms of energy performance, environmental and financial results by the tools described in Chapters 5, 7 and 8.

# 5. Energy performance

## 5.1. Concept and methodology

For energy performance, tools and approaches with different levels of complexity were considered including e.g. a simple approach based on U-values and heating degree days (HDD), the Be18 tool used to document compliance with the Danish Building Regulations (Aggerholm, 2018), and EnergyPlus (National Laboratory of the Rockies (NLR), u.d.). The HDD approach works best when used for individual retrofit measures rather than combinations of interacting measures, while Be18 is not Open Source. EnergyPlus was regarded as too complicated to include in the toolkit. The ClimaPlus tool (MIT, u.d.) developed at MIT primarily for educational use was considered as well, due to its simplicity. However, FuturHist would be dependent on adjustments by the developers to make it directly usable for the FuturHist toolkit, and the developers told that it was about to end, for which reasons it was opted out. Instead pyBuildingEnergy (PBE) (Eurac Research, 2025a) was considered. Based on preliminary tests of its usability and input requirements it was regarded as suitable to become part of the FuturHist toolkit.

PBE is an open-source Python library for building energy performance simulation. It was developed by Eurac Research (researchers not part of the FuturHist consortium) and is intended – based on building description, climate data, and HVAC-system definitions - to provide standardized calculations of building energy demand, comfort, and HVAC system performance. The tool is built around the European Energy Performance of Buildings (EPB) standards supporting that all relevant aspects for estimating energy performance are covered. The standards include EN ISO 52016-1:2017 Building energy needs for heating and cooling (European Committee for Standardization (CEN), 2017b), the EN ISO 52000 framework on overall energy performance assessment (European Committee for Standardization (CEN), 2017-2023), EN ISO 52010 on external climatic conditions (European Committee for Standardization (CEN), 2017c), the EN 15316 series on HVAC systems, generation, storage, distribution, and emission systems (European Committee for Standardization (CEN), 2017d), EN ISO 16798 on Ventilation and indoor environmental quality (European Committee for Standardization (CEN), 2017-2025), and EN ISO 12831 on heating load and domestic hot water calculations (European Committee for Standardization (CEN), 2017e).

PBE is available as a Python package (Eurac Research, 2025a) and on GitHub (Eurac Research, 2025b). The tool was developed within the European projects Infinite (EU Horizon 2020, grant agreement No. 958397, active 2020-2025) and Moderate (Horizon Europe, grant agreement No. 101069834 active 2022-2026).

Calculations with PBE require the user to define parameters covering:

- Location (to define weather data)

- Geometry (building height, area of roof, facades etc.)
- Thermal zones
- Walls, roofs, floors, windows (size, orientation, thermal capacity etc.)
- U-values and thermal bridges
- Internal gains (occupancy, equipment, lighting)
- Heating and cooling profiles
- Ventilation (air change rate and profile)
- Setpoint temperatures for heating and cooling.

A complete list of input parameters is shown in Annex 12.3.

The user defines a main thermal zone and optionally additional zones and boundary conditions. Walls are supposed to be defined as: opaque, transparent, adiabatic, and adjacent-zone boundaries. This controls how heat transfer is calculated.

As default weather can be obtained from PVGIS APIs (European Commission, 2025) or EPW weather files (Ladybug Tools LLC, 2025). However, PBE can handle any set of weather data, if they are formatted correctly. Refer to PBE documentation for further details (Eurac Research, 2025a).

The core engine calculates hourly or monthly heating demand, hourly or monthly cooling demand, indoor temperatures and heating and cooling loads. The calculations are performed per thermal zone according to ISO 52016 methodologies (European Committee for Standardization (CEN), 2017b).

A preliminary test was conducted using the Spanish demo case to test PBEs usability and its accuracy towards more detailed calculations performed in WP5. This involved the ENCOME user interface (Eurac Research, 2025c) being part of the PBE package. As this test gave promising results further studies of the functionality and requirements for input were performed (Chapter 5.3).

## 5.2. Development

### 5.2.1. Adjustment of pyBuildingEnergy (PBE)

PBE comes with the user interface ENCOME (Eurac Research, 2025c), however as part of developing the toolkit, FuturHist develops a new user interface integrating the energy calculator into the toolkit. Therefore – and because the ENCOME user interface was not updated to the latest version of PBE – analysing and testing the feasibility of the tool was based on the program code

written in Python, included in the PBE library (Eurac Research, 2025a), using input data representing the different demo cases.

No development as such of PBE took place in FuturHist, however EURAC implemented updates of the program code in the Spring/Summer of 2026. The updated version of PBE handles multi-zone buildings and follows a simplified EnergyPlus-like logic, where convective heat exchange is also calculated between adjacent thermal zones with different setpoint temperatures. As these updates took place in parallel with the testing of PBE in FuturHist, testing was based on a version of the Python code before these updates were implemented, to not interrupt the testing phase. Further it was the aim to keep the calculations within the FuturHist toolkit simple to limit the number of required input data, e.g. by using a single-zone approach when describing the building in question, which meant that the latest version of the Python code – using a multi-zone approach – was not necessary to include. By consulting the developer of PBE it was assured that this decision would not hamper the use of PBE. The implementation of the energy calculations in the toolkit is explained in deliverable D4.1 ‘Multidimensional decision-making methodology to identify an optimised solution for deep renovation of historic buildings’ (Sand, et al., 2026) and D4.3 ‘Digital step-by-step toolkit (draft)’.

As part of preparing for the feasibility test of PBE, preliminary tests were made to identify how sensitive the result was to the input data. A major finding was that the result did not include DHW, although the Python code includes program lines covering DHW. As in some cases the reference calculations performed as part of WP5 did include DHW (Sweden and Poland) it was relevant to understand whether PBE handled DHW and to which extent input data for dealing with this, was necessary. The dialogue with one of the developers of PBE (Daniele Antonucci, EURAC; not a part of the FuturHist consortium) confirmed that DHW is not included as standard in the space-heating and cooling calculation.

Instead, as a simple approach energy used for DHW [kWh] can be calculated as:

$$Q_{DHW} = c \times 1000 \text{ kg/m}^3 \times \frac{1}{3600 \text{ kJ/kWh}} \times \frac{1}{1000 \text{ l/m}^3} \times (T_{hot} - T_{cold}) \times A$$

where

- $c$  is the specific heat capacity for water [kJ/(kg K)]
- $A$  is the amount of water to be heated [l]
- $T_{hot}$  is the temperature of hot water [°C]
- $T_{cold}$  is the temperature of cold water [°C]

This will not include any losses in the storage and distribution system, and losses relate to the efficiency of the boiler, but at the same time we do not consider the contribution of these losses to heating the building.

Also, other issues were identified that needed to be clarified to understand how PBE works (adiabatic surfaces, efficiency of active systems), as they did not seem to be active when working with the PBE Python script. These issues are to be fully uncovered at a later stage, when preparing the final version of the FuturHist toolkit, due to a busy schedule at EURAC. Not including the efficiency of active systems as part of a retrofit is the reason for the use of 'energy need' rather than 'energy demand' in the rest of this chapter. To be able to handle a building being part of a continuous row of buildings (i.e. not being a free-standing building) in the feasibility test of PBE, adiabatic surfaces (walls towards neighbouring buildings) were handled by setting the area of these to 0.01 m<sup>2</sup> (0 was not allowed), although this approach disregards the thermal capacity of these walls.

Finally, preliminary tests showed that adding the parameters "solar\_shading\_transmittance" and "solar\_shading\_activation\_irradiance\_W\_m2" (not included in the example file in the PBE library), was decisive for getting meaningful results (when comparing with results from WP5) for those cases where cooling was necessary and solar shading was part of the building.

## 5.2.2. Setting up archetype models

As part of the development, archetype models were prepared, representing the different typologies identified in FuturHist and described in deliverable D1.2 'Building typology: analysis of the building stock and typologies definition'.

As these typologies for some parameters (esp. building size and U-values) cover a certain range of values, it might not be sufficient with one building archetype per typology. However, as a first step, to prepare an operable version of the toolkit, it was decided in the FuturHist consortium to collect one set of input parameters for each typology, engaging WP5 partners. Users of the FuturHist toolkit would still have the possibility – after having selected a relevant typology – to add their own values in case they represent better the actual building. It was also decided that archetypes preferably should be based on real buildings rather than imaginary buildings based on min/max/average values e.g. for building size and U-values. Basing archetypes on real buildings rather than using extreme values was considered better to ensure representativity and ensure that the values for the different input parameters would fit to each other. Also, users could probably better relate to real buildings.

WP5 technical partners (EURAC, PK, WHITE, STRATH) and demo case partners (AVRA, KRAKOW, SVK, EWH) were engaged to ensure that it was possible with a reasonable effort to collect the relevant data for performing a simulation using PBE based on the demo cases involved in FuturHist, as it was expected to be easier to collect data for typologies that included a FuturHist demo case than the other typologies. This was also done to test how easy it would be to add more typologies to the toolkit after finishing the FuturHist project.

Furthermore, as part of evaluating the implementation of PBE within the FuturHist toolkit, the full set of input parameters was systematically screened and divided into two groups: (i) parameters

with a substantial impact on model outputs, for which user-defined values are required, and (ii) parameters that can be represented using predefined default values derived from legislation, standards, or accepted engineering practice. The purpose of this classification was to streamline model creation and reduce the data-input burden without materially affecting the reliability of the results.

For typologies represented by a demo case, a set of input data was based on the geometry etc. of the specific demo case, representing both the baseline scenario and an ideal scenario in terms of energy saving. These were used to test PBE against more complex calculations performed as part of WP5, as described in Chapter 5.3.

To some extent demo cases do not fully represent the typology:

- For Spain (Casa de pisos: Spanish terraced tenement building, 1600-1920) there is no difference.
- Poland:
  - A typical building of the Polish typology Kamienica (Polish terraced tenement building, 1750-1945) would be part of a continuous urban block or street frontage, with adjacent buildings on both sides. In the demo case, the building is adjacent to another building on one side, but this neighbouring building is lower. As a result, part of the side wall is exposed to the outdoor environment, which affects the thermal boundary conditions and the energy performance calculation.
  - Further, the windows in the demo case have been renovated ( $U = 0.7 \text{ W/(m K)}$ ), while the typology would have double-glazed windows ( $U = 2.5 \text{ W/(m K)}$ )
  - The heating system is different; however this is not handled in the PBE models at present. The demo case has a gas boiler for space heating and an electric boiler for domestic hot water. Often in these kinds of buildings, space heating is provided by traditional ceramic tile stoves equipped with electric heating inserts. Domestic hot water is typically provided electrically.
- For Sweden (Monumentalbyggnad: Swedish monumental public building, 1850-1920) the typology does not have added roof insulation, while this is the case for the demo case. This gives a difference in U-value for the typology ( $0.58 \text{ W/(m K)}$ ) and the demo case ( $0.27 \text{ W/(m K)}$ ). PBE is therefore tested on the typology, not the demo case.
- For Scotland (Georgian tenement: Scottish Georgian terraced tenement building, 1750-1850), the demo case covers one monitored apartment and its airflow, and profiles are based on observed patterns. Calculations in WP5 however cover a whole block with four apartments, with a fixed air change rate, and a standardised occupancy and heating profile. Calculations with PBE mimics this baseline.

For typologies without a demo case, as a first step, a representative building was identified as follows for the four DC countries, showing different approaches in selecting these:

- For Spain a representative building is to be selected based on a sample of 11 buildings within the typology 'Patio de vecinos: Spanish terraced courtyard tenement building (1600-1920)' managed directly by AVRA and thoroughly documented. This takes place at a later stage of the project.
- Many buildings in Krakow are typical for the typology 'Willa miejska: Polish garden-city/urban villa (1900-1945)'. A specific building was selected together with the Municipality of Krakow (ZBK), who owns the building and was able to provide detailed technical information.
- For Sweden the description of an archetype was based on "Smalhus, tegelmurverk" in (Björk, et al., 1983) representing the typology 'Flerbostadshus funktionalism: Swedish functionalist multi-family housing block (1920-1945)'.
- For Scotland, a building that exhibited the most typical features such as bay window, one-over-one sash and case windows – i.e. one pane of glass in the top sash over one pane of glass in the bottom sash – and front door combined with a fanlight was selected to represent the typology 'Victorian terraced house: Scottish Victorian terraced house (1850-1920)'.

Input data for the different archetypes, each representing a typology, are given in Annex 12.4. Based on these, PBE models (Python scripts) are prepared for the FuturHist toolkit (not included in this deliverable). For the typologies without a Demo case, PBE models are still missing as input data is not yet complete. This will be part of the further development of the FuturHist toolkit, building upon the draft version presented in deliverable D4.3 'Digital step-by-step toolkit (draft)'. This will also include the final PBE models for typologies with a demo case after handling the issues presented in chapter 5.2.1.

## 5.3. Testing

PBE is tested towards results based on more advanced tools used in WP5 to indicate whether it gives sufficient robust results for early decision support. The comparison of results with PBE and from WP5 will focus on the reduction in energy need when comparing baseline and ideal case scenarios. Due to the limited number of cases, it is a feasibility test, not a validation of PBE, as this took place in parallel with further development of PBE by EURAC.

### 5.3.1. Preparing the feasibility test

To analyze and test PBE independently of the ENCOME user interface, a reference Python script from the PBE library was adapted for the case studies, although this meant manually inserting

input data at the correct places in the script. Country-specific model files were created for both baseline (before retrofit) and ideal scenarios by replacing default values with the relevant input data. The models were run in the Google Colab environment (Google, 2026) using PBE files available from the PBE GitHub repository (Eurac Research, 2025b). The model files were tested and iteratively revised to resolve coding errors and accommodate input updates and modelling constraints identified during the analysis.

WP5 partners were involved in compiling the input, including partners with experience with simulation tools (EURAC, PK, WHITE, STRATH) supported by partners with detailed knowledge of the demo cases (AVRA, KRAKOW, SVK, EWH). For Spain and Poland, the scenarios involved in the test were based on the demo case, while for Sweden and Scotland they were based on the typologies, to mirror what was done in WP5 calculations. However, as the purpose of the test was to compare the outcome of PBE with tools offering more detailed calculations, and not to compare between cases / typologies, this was of no importance for the outcome of the feasibility test.

### 5.3.2. Overall adjustments

The PBE Python script includes program lines for both HVAC and DHW. However, the HVAC part is only relevant when assessing energy use and not when looking at energy need acc. to ISO 52016 (European Committee for Standardization (CEN), 2017b). And as explained in Chapter 5.2.1, the PBE calculation does not handle DHW at present. The feasibility test therefore focused on using the correct data for building geometry, U-values, etc. Further, PBE does not handle whether the energy source is e.g. a gas boiler, district heating, or a heat pump. Therefore, the feasibility test is based on 'energy need' rather than 'energy demand' (which would include e.g. the efficiency of an active system).

Adiabatic surfaces are handled in a simple way, not taking the thermal capacity of the wall into consideration, cf. Chapter 5.2.1. This is relevant for Spain, Scotland, and to some extent for Poland (specified below).

Windows in a façade were grouped and modelled as a single window with the actual height and the width based on the total area of windows in a façade. In case windows with substantial different height are involved, it might be relevant to split up windows in a façade in more groups. This is not the case in the tested demo cases.

PBE does not handle sloping roofs, although all demo cases did include these. The sloping roofs were handled as flat roofs, not changing the area of the roof surface, i.e. the area became larger than the footprint of the building.

PBE handles vertical surfaces oriented either towards North, East, South, or West. More complex geometries, involving surfaces oriented in other directions, e.g. towards Southwest, as in the Polish demo case, must be treated by using one of the four main directions. As PBE is to be used to compare scenarios before and after retrofit, this simplification is not seen as critical.

### 5.3.3. Case specific adjustments

For the different demo cases further adjustments were made when testing the feasibility of PBE:

Spain:

- As the ground floor was not occupied and mainly consisted of an arcade and a courtyard 'slab to ground' was represented by the floor between first floor and the arcade, an approach that was also used in WP5. Compared to a similar building with no arcade the presence of an arcade will increase the transmission loss as it has more surface towards the outside. However, by using the same approach as in WP5 it was possible still to use this case to test the feasibility of PBE.
- The roof surface was a combination of flat and sloped roof. Both were treated as flat roofs, in both cases using the actual area of the surface. This was expected to have less effect on the result than if the roof area was projected to a horizontally surface, reducing the roof area.
- For 'solar shading transmittance' and solar shading activation irradiance' default values are used.
- For other shading parameters values were given by Spanish partners.

Poland

- Only the heated floors were included in the calculation (ground floor and first floor), which meant that U-value of the slab to ground was replaced with the U-value of the floor towards the basement. This overestimates to some extent the transmission loss as the basement will have a temperature somewhere between the ground floor and the basement.
- The demo case has neighbouring buildings that are lower, i.e. surrounding walls (gables) were to some extent exposed to the outdoor environment. For the remaining area of the gables the simple approach not taking thermal capacity into consideration was used to represent adiabatic surfaces.

Sweden

- Solar shading at the South façade (activated by sunlight, reducing the g-value) is quite common in buildings of this typology, however not included in the feasibility test to simplify the calculations. Leaving out solar shading will probably affect the energy need in both directions, overestimating the need for cooling in the summer period but underestimating the need for heating in the heating period.

## Scotland

- Only the heated floors were included, disregarding the basement, regarding the ground floor as 'slab to ground'. This is a simplification, as the basement, although not heated, still functions as a buffer thermally as in the Polish case. Therefore, the energy need for heating is probably overestimated.

Due to these simplifications and operating with only one thermal zone for the building in question, the energy need using PBE is not expected to be fully comparable with more detailed calculations performed in WP5. However, still the reduction in energy need is expected to be comparable with WP5 results.

Input parameters needed to calculate the energy need for heating and cooling (kWh/year) using PBE are included as Annex 12.3.

## 5.4. Results and discussion

PBE expresses the energy performance of a building as energy used for heating and cooling (kWh per month or year). However, as the aim is to reduce energy use it is the reduction in energy need when comparing base line and ideal scenarios that is interesting, not the specific energy need for heating and cooling.

### 5.4.1. Reduction in energy need

Table 9 - Table 12 therefore presents the energy need for heating and cooling for each of the four demo cases / typologies as well as the reduction in energy need. Results both when using PBE and the more advanced tools used in WP5 are shown, for comparison. Apart from the results for Poland based on WP5 calculations, DHW is excluded in all cases.

Looking at the *reduction in energy need* (kWh/year), PBE – using a limited amount of input data – seems capable of comparing scenarios, identifying the same tendencies in energy saving as more advanced tools used in WP5.

The results based on PBE and more detailed tools (WP5) are in line for Spain, Poland and Sweden, however not for Scotland. This is surprising as the Scottish case is quite simple and DHW is not included. On the other hand, the results for the Scottish baseline scenario for PBE and WP5 are very close, implying that the ideal scenario is dealt with differently in the two calculations (PBE and WP5). One difference is that the PBE model only includes heated floors, i.e. not considering that the insulation of the slab to ground (in the basement) was improved in the ideal scenario; however, this could not be the only explanation. Also, there seems to be an issue with the occupancy profile for the Scottish case, as data from the Scottish partner (STRATH) refers to the master bedroom, probably not representative for the apartment as such, thereby overestimating the energy need. However, this will be the case in both the baseline and ideal scenario.

Table 9. Energy need for heating and cooling (kWh/year) using PBE and WUFI Plus (WP5) on Spanish demo case representing the typology 'Casa de pisos: Spanish terraced tenement building (1600-1920)'.

|                             | Energy need for heating (kWh/year) | Energy need for cooling (kWh/year) | Sum (kWh/year) | Reduction in energy need (%) |
|-----------------------------|------------------------------------|------------------------------------|----------------|------------------------------|
| <b>Baseline (PBE)</b>       | 10071                              | 10566                              | 20637          | -                            |
| <b>Baseline (WP5)</b>       | 7806                               | 8742                               | 16548          | -                            |
| <b>Ideal scenario (PBE)</b> | 2988                               | 6977                               | 9965           | 51.7                         |
| <b>Ideal scenario (WP5)</b> | 2096                               | 6190                               | 8286           | 49.9                         |

Table 10. Energy need for heating and cooling (kWh/year) using PBE and DesignBuilder (WP5) on Polish demo case representing the typology 'Kamienica: Polish terraced tenement building (1750-1945)'.

|                             | Energy need for heating (kWh/year) | Energy need for cooling (kWh/year) | Sum (kWh/year) | Reduction in energy need (%) |
|-----------------------------|------------------------------------|------------------------------------|----------------|------------------------------|
| <b>Baseline (PBE)</b>       | 81179                              | -                                  | 81179          | -                            |
| <b>Baseline (WP5)</b>       | 81921                              | -                                  | 81921          | -                            |
| <b>Ideal scenario (PBE)</b> | 25176                              | -                                  | 25176          | 69.0                         |
| <b>Ideal scenario (WP5)</b> | 30857                              | -                                  | 30857          | 62.3                         |

Table 11. Energy need for heating and cooling (kWh/year) using PBE and IDA-ICE (WP5) on Swedish demo case representing the typology 'Monumentalbyggnad: Swedish monumental public building (1850-1920)'.

|                             | Energy need for heating (kWh/year) | Energy need for cooling (kWh/year) | Sum (kWh/year) | Reduction in energy need (%) |
|-----------------------------|------------------------------------|------------------------------------|----------------|------------------------------|
| <b>Baseline (PBE)</b>       | 183613                             | -                                  | 183613         | -                            |
| <b>Baseline (WP5)</b>       | 201477                             | 2721                               | 200184         | -                            |
| <b>Ideal scenario (PBE)</b> | 117726                             | -                                  | 117726         | 35.9                         |
| <b>Ideal scenario (WP5)</b> | 119186                             | 2894                               | 118066         | 41.0                         |

Table 12. Energy need for heating and cooling (kWh/year) using PBE and esp-r (WP5) on Scottish demo case representing the typology 'Georgian tenement: Scottish Georgian terraced tenement building (1750-1850)'.

|                             | Energy need for heating (kWh/year) | Energy need for cooling (kWh/year) | Sum (kWh/year) | Reduction in energy need (%) |
|-----------------------------|------------------------------------|------------------------------------|----------------|------------------------------|
| <b>Baseline (PBE)</b>       | 39453                              | -                                  | 39453          | -                            |
| <b>Baseline (WP5)</b>       | 40831                              | -                                  | 40831          | -                            |
| <b>Ideal scenario (PBE)</b> | 19089                              | 260                                | 19349          | 51.0                         |
| <b>Ideal scenario (WP5)</b> | 13664                              | -                                  | 13664          | 66.5                         |

Surprisingly, temperature profiles for outdoor temperatures (monthly average) differ between PBE and WP5, esp. during winter, which explains to some extent the differences in energy need. Differences can go both ways. For example, in the Polish case January, February and March is represented by -1.0 °C, 0.6 °C and 4.1 °C in WP5 and 3.2 °C, 3.6 °C and 3.8 °C in PBE, while in the Scottish case, the figures are 4.7 °C, 4.9 °C and 6.7 °C in WP5, and 3.0 °C, 4.1 °C and 1.0 °C in PBE. How this affects the results has not been analysed further. Other kinds of assumptions made for WP5 calculations and calculations with PBE might differ as well, although this has not been investigated further.

When looking at the *energy need* results (kWh/year) *before and after intervention*, results with PBE are in most cases not that far from results from WP5, implying that PBE even with the assumptions and simplifications described in Chapter 5.3, gives reasonable results. The outlier is the ideal scenario for Scotland, where the energy need using PBE is 43 % higher than given by WP5. In the Spanish and Scottish case PBE gives a higher result than WP5 in both cases, while it gives lower results for Poland and Sweden. Again, this should not be overinterpreted due to the simplifications made using PBE and the use of different tools for the detailed calculations in WP5, cf. Table 9 - Table 12, based on what is widely used for energy simulations either by the partners or on a national level.

### 5.4.2. Energy need per heated square meter

Table 13 and Table 14 shows the energy need expressed in kWh/year per heated m<sup>2</sup>. In the baseline scenario, the energy need per m<sup>2</sup> is highest in the Spanish and Polish case, while in the ideal scenario the energy need is highest in the Spanish and Swedish case. This has to do with the difference in reduction in energy need between the cases, cf. Table 9 - Table 12. Comparison between the demo cases based on Table 13 and Table 14 should be done carefully as the differences between results based on PBE and WP5 are not consistent in terms of whether PBE or WP5 giving the highest results, cf. Table 9 - Table 12. None of the results in Table 13 and Table 14 includes DHW, due to the simplification of calculations using PBE.

Table 13. Energy need (kWh/year/m<sup>2</sup> heated area) in the baseline scenario for the four demo cases using PBE.

| Baseline scenario | Energy need for heating (kWh/m <sup>2</sup> /year) | Energy need for cooling (kWh/m <sup>2</sup> /year) | Sum (kWh/m <sup>2</sup> /year) |
|-------------------|----------------------------------------------------|----------------------------------------------------|--------------------------------|
| Spain             | 63.9                                               | 67.1                                               | 131.0                          |
| Poland            | 121.8                                              | -                                                  | 121.8                          |
| Sweden            | 91.8                                               | -                                                  | 91.8                           |
| Scotland          | 79.6                                               | -                                                  | 79.6                           |

Table 14. Energy need (kWh/year/m<sup>2</sup> heated area) in the ideal scenario for the four demo cases using PBE.

| Ideal scenario | Energy need for heating (kWh/m <sup>2</sup> /year) | Energy need for cooling (kWh/m <sup>2</sup> /year) | Sum (kWh/m <sup>2</sup> /year) |
|----------------|----------------------------------------------------|----------------------------------------------------|--------------------------------|
| Spain          | 19.0                                               | 44.3                                               | 63.3                           |
| Poland         | 37.8                                               | -                                                  | 37.8                           |
| Sweden         | 58.7                                               | -                                                  | 58.7                           |
| Scotland       | 38.7                                               | 0.5                                                | 39.2                           |

### 5.4.3. Implications from testing PBE

As the number of cases involved in the test of PBE presented in this chapter is limited, the test presented is a feasibility test, not a validation of PBE. The computational core of PBE has already been validated as part of the development of the tool, comparing it with more advanced tools.

A major observation, looking at the *reduction in energy need* (kWh/year), is that PBE – using a limited amount of input data – seems capable of comparing scenarios, identifying the same tendencies in energy saving as more advanced tools, such as WUFI Plus, DesignBuilder and IDA-ICE. Further, the feasibility test does check whether building data collected in FuturHist can be represented, and whether the typologies can be modelled despite PBE's limitations.

Based on these results – showing the potential of using PBE in the early decision phase when considering renovating a building – the archetype models for the typologies with a demo case are implemented in the draft version of the FuturHist toolkit, as described in deliverable D4.3 ‘Digital step-by-step toolkit (draft)’.

Regarding the issues pointed out in Chapter 5.2.1 (DHW, adiabatic surfaces, etc.) that affects the accuracy of using PBE, it is intended to handle this in the final version of the FuturHist toolkit.

Another issue is to ensure that the same weather data are used for early-stage calculations and decisions based on the FuturHist toolkit and more detailed calculations at a late stage, to avoid a potential source of error.

FuturHist KPIs related to energy are: ‘Non-renewable primary energy demand’ and ‘Non-renewable primary energy savings’. However, at present PBE does not focus on whether the energy is renewable or not. That is a question of energy production and energy demand, rather than energy need, as used as indicator in the feasibility test presented here. This will be a possible task for future improvement to strengthen the link between PBE and the KPIs.

## 6. Indoor environmental quality

### 6.1. Concept and goals

The tool targeting indoor environmental quality is purely for educational purposes for the user, and will not, as other tools, provide calculations. The tool is therefore in the form of a guide developed in layman's terms, which will be available to the user both in the “guide module” in the step-by-step user experience and in the end report. The content of the tool can be found in Annex 12.5. This annex also includes the references used in this chapter.

The following sections will discuss the different guidelines and thresholds for different IEQ parameters, providing a reason as to why they were selected for the KPIs of the project. Furthermore, it will provide the role of the guide related to IEQ. See deliverable D4.1 ‘Multidimensional decision-making methodology to identify an optimised solution for deep renovation of historic buildings’ (Sand, et al., 2026) for detailed information about how this guide is incorporated into the toolkit.

### 6.2. Implementation into the toolkit

The guide is structured around three levels of technical resources: understanding, screening, and technical assessment. Although the IEQ could be relevant to any of these levels, its placement was carefully considered. Due to the implications for additional monitoring resources and the necessity of interpreting data to assess retrofit impacts, the guide focuses primarily on general understanding.

The IEQ guide serves as an accessible educational resource designed to help users understand how retrofit interventions may affect the indoor environment and influence retrofit strategy decisions. It introduces key aspects of IEQ, including thermal comfort, indoor air quality, and ventilation, as defined by the FuturHist project KPIs. Instead of providing technical calculations, the guide offers practical guidance on building fabric and IEQ, translating these concepts into actionable information. It assists users in recognising potential risks and best practices, as well as identifying situations where further investigation or specialist assessment may be necessary. The guide adopts a primarily qualitative approach to ensure accessibility for users without specialist monitoring equipment or expertise in environmental data interpretation.

Accordingly, the content is presented in accessible language while maintaining accuracy to support informed decision-making. The guide is not intended to serve as a specialist assessment, professional advice, or detailed instruction on monitoring and interpreting IEQ data. It supports informed retrofit decisions by highlighting key indicators, common issues, and potential relationships between building fabric and IEQ parameters, as well as identifying when further

investigation or specialist advice is needed. Additionally, the guide aims to align energy performance improvements with the conservation of historic buildings, taking into account the health, comfort, and wellbeing of occupants.

The guide supports a whole-building approach to retrofit by encouraging consideration of building fabric, indoor environmental conditions, building services, and occupancy patterns collectively. Its purpose is to raise awareness, facilitate early-stage decision-making, and highlight best practices rather than prescribe a single solution. This approach is particularly relevant for historic buildings, where construction methods, materials, heritage significance, climate, and usage patterns can vary significantly.

The IEQ Guide adopts a predominantly qualitative approach, grounded in three key considerations. First, quantitative assessment of indoor environmental conditions through building performance evaluation can provide valuable evidence but necessitates reliable measurement equipment, appropriate sensor placement, representative monitoring periods, and careful interpretation. Second, individual measurements may be misleading without contextual information on outdoor conditions, occupancy, building operation, and seasonal variation. Third, providing only numerical thresholds (i.e., annual mean) may create the false impression that complex IEQ conditions can be simply classified as "good" or "bad." Such an approach would require users to fully understand all influencing factors before analysing retrofit impacts, which exceeds the intended scope of the tool.

Another important consideration is that the use of specific sensors for monitoring IEQ conditions and building fabric may impact project economics, as additional equipment, installation, and professional costs could be required, potentially reducing accessibility. Consequently, the guide enables users to recognise indicators of potential problems, pose relevant questions, and determine when more detailed investigation may be justified.

This qualitative approach is not intended to discourage measurement. When monitoring data are available, or when initial building walkthroughs identify concerns such as mould, dampness, inadequate ventilation, overheating, or poor IAQ, further quantitative investigation may be necessary to determine causes and develop mitigation strategies during retrofit. The guide recommends that monitoring be considered a targeted next step where appropriate, rather than a prerequisite for every user or building. When assessing IEQ conditions, threshold values should be interpreted in relation to seasonal or annual trends rather than assessed as absolute values, and the values presented in chapter 6.3 could be used to inform these values.

## 6.3. IEQ guidelines

### 6.3.1. Temperature

Indoor temperatures are usually measured to calculate thermal comfort, overheating and the temperature impact on indoor material emission rates (Haghighat and De Bellis, 1998),

perceptions of IAQ (Fang et al., 1998) and health in terms of temperature extremes (Neill and Ebi, 2009). Research shows that comfort decreases at high temperatures, leading to sleep disturbances and, as a result, lower productivity, decreased attentiveness, and impaired judgment (Peacock et al., 2010). Measurements have been taken on issues related to overheating in low-energy homes (McGill et al., 2016) and contextualised within IAQ (Moreno-Rangel, 2019; Moreno-Rangel et al., 2018).

One of the most accepted definitions of overheating is “[...] *the phenomenon of excessive or prolonged high temperatures in the home, resulting from internal or external heat gains, which may have adverse effects on the comfort, health or productivity of the occupants*” (Zero Carbon Hub, 2015, p. 11). Different criteria are used to evaluate the risk of overheating, employing either static or dynamic values, as described below. However, no universal definition of overheating exists (Zero Carbon Hub, 2012), and no accepted standard for the domestic sector has been established (Zero Carbon Hub, 2015, 2012). CIBSE TM59 standardises overheating assessment and relies on the criteria outlined in CIBSE Guide A and CIBSE TM52 (detailed below) to evaluate overheating. TM59 requires dynamic simulations of the building's construction and shading, as specified, using hourly data. It also recommends using standard occupancy patterns, ventilation assumptions, and window operation scenarios, all of which should be evaluated in accordance with the TM52 criteria. However, “[...] *real proof will come in future when the units tested are built and occupied* (Bonfigli et al., 2017, p. 1).”

Overheating is not solely a function of high temperature; other factors are involved (Nicol, 2004), especially in buildings without mechanical cooling (Nicol and Humphreys, 2002). The adaptive approach, described in CIBSE Guide A Section 1.6, considers outdoor temperatures from previous days, making it a dynamic benchmark. The CIBSE criterion is based on the maximum acceptable temperature range outlined in the TM52 category II (normal expectation for new and renovated buildings) (CIBSE, 2013):

- *Upper limit:*  $T_{max} = 0.33T_{rm} + 18.8 + 3$
- *Lower limit:*  $T_{min} = 0.33T_{rm} + 18.8 - 3$

The adaptive approach uses exponentially weighted outdoor running mean temperatures ( $T_{rm}$ ) over the monitoring period to define the acceptable temperature range.  $T_{rm}$  is calculated from the following equations:

$$T_{rm} = (T_{od-1} + T_{od-2} + T_{od-3} + T_{od-4} + T_{od-5} + T_{od-6} + T_{od-7})/3.8$$

$$T_{rm} = (1 - \alpha)T_{od-1} + \alpha T_{rm-1}$$

where  $T_{od-1}$  represents the daily mean outdoor temperature for the previous day,  $T_{od-2}$  the day before and so on;  $T_{rm-1}$  is the exponentially weighted running mean for the previous day, and the constant  $\alpha$  is 0.8.

The adaptive method presented in the TM52 characterises overheating in a building or room when it fails any two of the following criteria:

**Hours of exceedance.** This criterion limits the number of hours during which the operative temperature exceeds the threshold comfort temperature. It therefore refers to the temperature difference between the operative temperature and the maximum acceptable temperature ( $\Delta T$ ). This value should not be greater than or equal to 1°C for more than 3% of the occupied hours during the non-heating season (May to September).

**Daily weighted exceedance.** This criterion concerns the severity of overheating on any given day, which is as important as the frequency of overheating. The criterion is met when the daily limit for weighted exceedance ( $W_e$ ) during occupied hours is less than or equal to the daily limit.  $W_e$  is calculated using the following equations:

$$W_e = \sum (h_e \times WF)$$

$$\therefore W_e = (h_e \times 0) + (h_{e1} \times 1) + (h_{e2} \times 2) + (h_{e3} \times 3)$$

**Upper-temperature limit** refers to the maximum daily temperature for a room/building. Hence,  $\Delta T$  should not exceed 4°C at any time.

Other overheating methods are based on static benchmarks. The Passive House Institute set a benchmark for overheating at 25°C for more than 10% of the year (Bere, 2013; Hopfe and McLeod, 2015). Other work by CIBSE sets overheating criteria at 25°C in living areas and 23°C in bedrooms for no more than 5% of the occupied hours, and the other benchmark is set at no more than 1% of the annual occupied hours over the operative temperature of 28°C for living areas and 26°C for bedrooms (CIBSE et al., 2006). While all these methods are available, this guide uses 25°C as the reference based on the FuturHist project's KPIs.

### 6.3.2. Relative humidity

In IAQ studies, relative humidity helps determine the risk of mould growth, dampness, or the proliferation of house dust mites and other invertebrates. Moreover, relative humidity affects indoor material emission rates (Haghighat and De Bellis, 1998) and IAQ perception (Fang et al., 1998) in a manner similar to temperature. Relative humidity is the “[...] *ratio of water vapour pressure to the saturation of water pressure (over water) at a gas temperature*” (Vaisala Oyj, 2013, p. 3).

Usually, IAQ should be “dry and cool” for material emission (VOCs, ozone, and particulate) testing in climatic chambers (Wolkoff and Kjærgaard, 2007), but in real-life situations, building occupants may develop symptoms of irritation. Recent research indicates that low indoor relative humidity can lead to symptoms of Sick Building Syndrome (SBS), including eye irritation, dry skin, and mucosal discomfort (Doty et al., 2004). For example, when relative humidity drops below 20% RH, it has been linked to eye irritation and dry skin (Arundel et al., 1986), and levels below 30% RH

may cause respiratory problems due to dry mucous membranes (Burton, 1962). Additionally, note that 40% RH is better for eye and upper airway health than 30% RH (Sunwoo et al. 2006).

High relative humidity levels are associated with the growth of mould, allergenic mites, and fungi, along with increased concentrations of formaldehyde, sulphur, and nitrogen dioxide acids and salts in the air (Arundel et al., 1986). (Berglund et al. 1992) suggests that mould growth risk rises above 70% RH, with laboratory studies showing growth at 75-95%RH depending on the substrate (Nielsen et al., 2004; World Health Organization Europe, 2009). Under typical temperatures, mould can grow in common building materials in homes when internal surface humidity reaches 78%RH or above (Johansson et al., 2013). While according to (CIBSE et al., 2015), mould growth corresponds to indoor relative humidity levels of 70% RH. Keeping humidity below 60%RH also prevents house dust mite growth (Wolkoff and Kjærgaard, 2007).

CIBSE recommends 40-70% RH for residential spaces, or optimally 65% RH for comfort (CIBSE et al., 2006). The EPA recommends that homeowners maintain relative humidity below 60% RH, with an ideal range of 30-50% RH (EPA, 2012). For this guide, we recommend a benchmark of 40-60% RH, as this best aligns with both CIBSE and EPA recommendations in accordance with FuturHist KPIs.

### 6.3.3. Carbon dioxide

CO<sub>2</sub> levels correlate with pollution from human occupancy but may not reflect other pollution sources, such as off-gassing from building materials. CO<sub>2</sub> levels are commonly used as indicators of ventilation (Porteous, 2011) and IAQ (Curwell et al., 1990). However, CO<sub>2</sub> is not considered an indoor air pollutant (Satish et al., 2012), despite observed negative effects on human well-being and productivity (Kajtar et al., 2006). A frequent practice is to use CO<sub>2</sub> as an indicator of ventilation rates (Wargocki, 2013), and levels below 1,000 ppm are associated with adequate solutions in this regard (Porteous, 2011), as human bio-effluents were considered the most significant pollutant of indoor air (Mølhave et al., 1997). CO<sub>2</sub> levels can be used as an indicator of IAQ levels (Persily, 1997, 1996). This practice remains prevalent today, especially when investigating crowded living environments (Wang et al., 2017). However, recent studies have shown that various parameters affect CO<sub>2</sub>, including its removal, building openings, and heat (Steiger et al., 2008). Therefore, a more sensible practice is to use CO<sub>2</sub> as a metric of outdoor air ventilation (Sundell et al., 2011).

Porteous (2011) found that CO<sub>2</sub> concentrations above 1,000 ppm are related to poor ventilation, corresponding to ventilation rates of 8l/s (Appleby, 1990) in residential buildings. Indoor CO<sub>2</sub> concentrations above 700 ppm of the outdoor level are considered acceptable indoor concentrations (ASHRAE, 2007). However, this relies on the assumption that outdoor CO<sub>2</sub> levels are truly acceptable (typically 300-500 ppm). Controlled ventilation is essential to achieve this goal, particularly in low-energy buildings that feature high airtightness (SCHER, 2007).

The 1,000 ppm benchmark is supported by associations among CO<sub>2</sub> levels, ventilation rates and health impacts. Ventilation rates of 10 l/s per person could effectively lower the prevalence of Sick

Building Syndrome and improve occupant satisfaction with IAQ (Godish et al., 1996). (Wargocki 2013, p.114) states that “ventilation rate in homes is associated with health in particular with asthma, allergy, airway obstruction and SBS symptoms [...] ventilation rates above  $0.4h^{-1}$  or  $CO_2$  below 900ppm in homes seem to protect against health risk.” For the purpose of this guide, the  $CO_2$  threshold is set at 1,000 ppm in line with the project KPIs.

### 6.3.4. Particulate matter $2.5\mu m$

Particulate matter 2.5 ( $PM_{2.5}$ ) refers to ultrafine particles or droplets measuring  $2.5\mu m$  or smaller in diameter. Their composition varies, but it includes materials referred to as dust, smoke, soot (AQEG, 2012), mineral ash released into the atmosphere includes coal and oil ash, metal oxides, calcium carbonate, sodium, chlorides, pollen, mould spores, as well as other airborne matter like hair, fur, fleece, and plant fibers such as cotton, flax, and hemp, along with silicate particles materials (i.e. zeolites, sepiolite clays), textile fibres (i.e. nylon, polypropylene, glass and ceramic, silicates, asbestos) (Crump et al., 2002). The impact of airborne particulate matter on human health is directly linked to particle size (Harrison et al., 2010). Prolonged exposure to  $PM_{2.5}$  can harm health, as respiratory diseases are closely linked to  $PM_{2.5}$  levels (Harrison et al., 2010).

The literature suggests that  $PM_{2.5}$  may lead to cataracts, eye irritation, redness, runny noses, respiratory issues, cancer, and cardiovascular diseases (Bernnan, 2015; Bruce et al., 2000; Mott et al., 1997; Secretaria de Salud, 2014) and hypertension (Holguín et al., 2003). Furthermore,  $PM_{2.5}$  can reach deep into the human respiratory system, leading to higher hospital admissions and premature deaths (WHO, 2000).

As concern about the effects of  $PM_{2.5}$  on human health increases (Kampa and Castanas, 2008), especially in residential buildings (Crump et al., 2009), different thresholds have been set for exposure. For instance, (Laxen et al. 2010) suggest that there is currently no safe level in the short or long term. Daily average exposure recommendations might be as low as  $8\mu g/m^3$  (Environment et al., 2003) or as high as  $25\mu g/m^3$  (Commission, 2015), but there is a general consensus that levels above  $15\mu g/m^3$  are considered harmful to human health based on recently published data from the WHO (WHO, 2021). For this reason, this guide suggests the  $PM_{2.5}$  exposure benchmark at  $15\mu g/m^3$  over a 24-hour period ( $5\mu g/m^3$  per year).

### 6.3.5. Total Volatile Organic Compounds

Volatile organic compounds (VOCs) are a broad, diverse and widespread group of substances that vaporise at room temperature. The indoor VOC mixture, commonly referred to as ‘total volatile organic compounds’ (tVOCs), includes organic compounds with boiling points ranging from  $20-100^\circ C$  to  $240-260^\circ C$ , as classified by the WHO (WHO, 1989). Previously, VOCs were hard to analyse individually as health hazards, so their health impacts were studied collectively as tVOCs (WHO, 1997). Therefore, studies made associations between health and the temporary exposure to tVOCs (Molhave et al., 1991), as well as their severity (Molhave, 1991). Nowadays, individual VOCs, such as formaldehyde and benzene, are associated with significant health risks

(WHO, 2010), and guidelines have been developed to target specific VOCs instead of tVOCs (Berglund et al., 1997; Mølhave et al., 1997; Teichman and Howard-reed, 2016).

Exposure to VOCs can lead to acute and chronic health effects (Maroni et al., 1995), such as respiratory conditions, neurotoxicity, lung cancer and eye and throat irritation (Hodgson et al., 1991; Maroni et al., 1995; Molhave, 1991; Mølhave et al., 1997; Molhave et al., 1991). Neurological effects encompass fatigue, headaches, dizziness, nausea, lethargy, and depression (Guo et al., 2004). The WHO has issued guidance on safe limits for individual VOCs (WHO, 2010, 2000), and a detailed list of specific VOC exposure limits is available at (Health and Safety Executive 2011; CIBSE 2011). Guidelines differ for tVOC levels in non-industrial settings, from 25 µg/m<sup>3</sup> (Berglund et al., 1997) to 500 µg/m<sup>3</sup> (Delia, 2012). However, it is broadly accepted that a maximum level of 300 µg/m<sup>3</sup> over an 8-hour period should be used. (ECA, 1992), which is the same as the UK guidelines (HM Government, 2013).

tVOC concentrations tend to be higher in newly constructed buildings because they release VOCs from construction materials and interior contents (Brown et al., 1994). Indoor organic compounds originate from various sources, including building materials like vinyl tiles, coving, carpets, linoleum, particleboard, and power cables, as well as construction products such as paints, paint thinners, paint strippers, adhesives, caulks, and cleaners. They are also linked to human activities, including frying food, smoking, dry-cleaned clothing, deodorants, showering, molds, pesticides, and personal care items (Zhang and Smith, 2003).

To convert tVOC concentrations from ppb to µg/m<sup>3</sup>, the following formula is used:

$$\text{Concentration } (\mu\text{g}/\text{m}^3) = \text{Concentration } (\text{ppb}) \times \frac{\text{Molecular mass } (\text{g}/\text{mol})}{\text{Molecular Volume } (\text{L})}$$

where the molecular volume is 24.45 L (assumptions @ 1atm and 25°C).

Molecular mass for tVOC is variable (40-150 g/mol) according to the composition, but a value of 100 g/mol was used for purposes of conversion, as assumed in experiments by (Khan & Kr. Ghoshal 2000).

## 7. Environmental values (LCA)

### 7.1. Concept and methodology

#### 7.1.1. Rationale for the development of the LCA tool

Within the multidimensional decision-making methodology of the FuturHist Integrated Planning Toolkit, Life Cycle Assessment (LCA) of greenhouse gas emissions serves as a fundamental Key Performance Indicator (KPI) under the "Environmental Values" dimension.

After researching existing tools that are used for LCA in building industry, it was concluded that their scope is too detailed for an early-stage toolkit. They usually require input for each specific part of the building, which are then mapped with emission factors per defined unit. Considering FuturHist approach that was relying on predefined solutions and typologies, it was necessary to develop a tool that can utilize this gathered knowledge.

#### 7.1.2. Method and required inputs

##### 7.1.2.1. Calculation method

The core calculation methodology adheres to the European Standard EN 15978 (European Committee for Standardization (CEN), 2012), and includes phases A1-A3, B4, B6, C3 and C4, as highlighted in Figure 18.

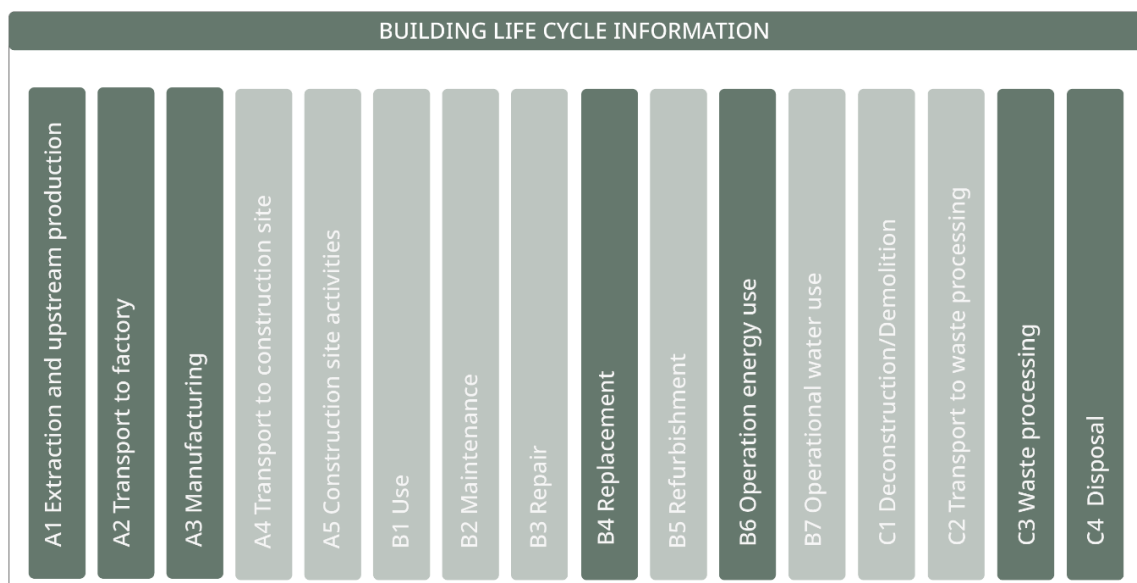


Figure 18. LCA stages, adapted from EN 15978 (European Committee for Standardization (CEN), 2012).

To calculate the KPI, FuturHist LCA tool calculates the baseline operational energy greenhouse gas emissions (B6 phase) over 50 years of use, using the results from the energy calculator (PBE), and compares it to a summary of embodied greenhouse gas emissions caused by selected solutions and operational energy emissions over 50 years of use after the solutions are implemented. These are calculated with results from the energy calculator with updated energy model which considers the selected solutions.

The main result is the difference in the emissions mentioned, expressed as a percentage of the baseline scenario. It can be described using the following formula:

$$GWP_{dif} = \frac{GWP_{energy,baseline} - ((\sum GWP_{sol} \times A_{sol}) + GWP_{win} \times A_{win} + (\sum GWP_{active} \times P) + GWP_{energy,improved})}{GWP_{energy,baseline}} \times 100 (\%)$$

Where:

|                         |                                                                                |
|-------------------------|--------------------------------------------------------------------------------|
| $GWP_{dif}$             | is resulting difference between carbon emissions ex-ante and ex-post scenarios |
| $GWP_{sol}$             | are GWP emissions from respective insulation solutions                         |
| $A_{sol}$               | is applied area for respective insulation solutions                            |
| $GWP_{win}$             | are GWP emissions from window solutions                                        |
| $A_{win}$               | is applied area for window solutions                                           |
| $GWP_{active}$          | are GWP emissions from active solutions                                        |
| $P$                     | is peak power of active solutions                                              |
| $GWP_{energy,improved}$ | are GWP emissions from energy use in the ex-post scenario                      |
| $GWP_{energy,baseline}$ | are GWP emissions from energy use in the ex-ante scenario                      |

Each of these elements in the formula will be described in more detail in the following subchapters.

#### 7.1.2.2. Databases – sourcing, formulation and mathematical principles

##### LCA insulation solutions database

The foundational database for material impacts relies on the German ÖKOBAUDAT platform (Federal Ministry for Housing, Urban Development and Building, n.d.). This repository provides comprehensive, scientifically validated lifecycle inventory data that strictly complies with the EN

15804+A1 (European Committee for Standardization (CEN), 2013) and EN 15804+A2 (European Committee for Standardization (CEN), 2019) standards.

In cases where a fitting dataset could not be found in ÖKOBAUDAT database, it was replaced with a relevant product-specific EPD. The decision to prefer generic datasets was made based on the early-stage nature of the tool, where information about the specific producer and type of product is typically lacking.

Fitting datasets from ÖKOBAUDAT or EPDs were attached to the defined materials in the defined build-ups. Following that is factoring the functional units to a single square meter of fitted system, also in a different thickness.

Mathematically, embedded carbon emissions of each part of the buildup can be described with the following formula, exemplified for a substructure:

$$GWP_{sub} = (f_{sub} \times (GWP_{sub,A1-A3} + GWP_{sub,C3} + GWP_{sub,C4})) \times [50 \div RSL_{sub}]$$

where

|                   |                                                                                                                                                                                          |
|-------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $GWP_{sub}$       | are GWP emissions for that part of the build-up                                                                                                                                          |
| $f_{sub}$         | is scaling factor for scaling database/EPD functional unit to a single square meter, or in cases where the thickness is variable, to a single square meter with one millimetre thickness |
| $GWP_{sub,A1-A3}$ | are GWP emissions for stages A1-A3, sourced from the dataset/EPD                                                                                                                         |
| $GWP_{sub,C3}$    | are GWP emissions for stage C3, sourced from the dataset/EPD                                                                                                                             |
| $GWP_{sub,C4}$    | are GWP emissions for stage C4, sourced from the dataset/EPD                                                                                                                             |
| $RSL_{sub}$       | is reference service life for that part of the build-up                                                                                                                                  |

The result of a solution is a summary of these for all three parts of the build-up:

$$GWP_{sol} = GWP_{sub} + GWP_{ins} + GWP_{fin}$$

where

|             |                                          |
|-------------|------------------------------------------|
| $GWP_{sol}$ | are GWP emissions for the given solution |
| $GWP_{sub}$ | are GWP emissions for substructure       |
| $GWP_{ins}$ | are GWP emissions for insulation         |
| $GWP_{fin}$ | are GWP emissions for finish             |

This formula and the input required are the basis for the insulation solutions database, which is attached as [Annex 12.6](#).

### LCA windows solutions database

Like the insulation solutions, window solutions were also split into parts: Glazing, Frame, and Coats/Sealings. The difference this time was that there were no solutions with variable thicknesses, meaning the scaling factor has account only for scaling to a single square meter.

The result of a solution is a summary of these for all three parts of the build-up:

$$GWP_{win} = GWP_{gla} + GWP_{fra} + GWP_{cs}$$

where

|             |                                          |
|-------------|------------------------------------------|
| $GWP_{win}$ | are GWP emissions for the given solution |
| $GWP_{gla}$ | are GWP emissions for glazing            |
| $GWP_{fra}$ | are GWP emissions for frame              |
| $GWP_{cs}$  | are GWP emissions for coats/sealings     |

This formula and the input required are the basis for the window solutions database. The database in its current form and completeness is attached as [Annex 12.7](#).

### LCA active solutions database

It is important to mention that the scope of the LCA for the active systems is limited only to large equipment, without distribution systems like heating surfaces, ventilation ducts, wiring, etc. as it would require information that is too extensive to include in an early-stage analysis, while it would reflect a marginal part of the total result.

Furthermore, scaling the datasets or EPDs is done linearly using power ratings of the system, as that is a variable that can be connected to the total emissions of the equipment piece (Caduff, et al., 2014).

The formula for calculating carbon emissions from active systems is:

$$GWP_{active} = f_{active} \times (GWP_{active,A1-A3} + GWP_{active,C3} + GWP_{active,C4}) \times [50 \div RSL_{active}]$$

where

|                |                                                                                           |
|----------------|-------------------------------------------------------------------------------------------|
| $GWP_{active}$ | are GWP emissions for the given solution                                                  |
| $f_{active}$   | are scaling factor for scaling database/EPD functional unit to a single kilowatt of power |

$GWP_{active,A1-A3}$  are GWP emissions for stages A1-A3, sourced from the dataset/EPD

$GWP_{active,C3}$  are GWP emissions for stage C3, sourced from the dataset/EPD

$GWP_{active,C4}$  are GWP emissions for stage C4, sourced from the dataset/EPD

$RSL_{active}$  is reference service life for the given solution

This formula and the input required are the basis for the active solutions database. Tested solutions and used values are attached as an [Annex 12.8.](#)

### LCA energy use emissions database

Calculating the environmental impact of the operational phase (Module B6) requires mapping distinct emission factors to the projected energy carriers of the building, across European countries (to the best ability), and through 50 years of reference study period. Databases were formed in two ways:

- **Electricity and Gas:** Electricity emission factors are mapped using the European Union reference scenario (European Commission, 2021), while natural gas and biomass calculations utilize a fixed emissions factor from another EU report (Bastos, et al., 2024).
- **District Heating:** Evaluating the impact of District Heating systems requires a complex structural dataset derived from the Heat Roadmap Europe 5 – HRE5 (Mathiesen, et al., 2026) scenario model combined with carbon emission datasets on energy use from ÖKOBAUDAT. Unlike standalone natural gas boilers or local heat pumps, district heating is not a single technology but rather a highly localized, dynamically evolving network of multiple energy sources. Some heat sources are treated as carbon-free, either because they are present as a waste heat source (high temperature industrial heat waste, for example) or because they are highly renewable with low or no need for additional heating (like direct solar collectors).

The foundation of this database are the individual emission factors for each heating source from ÖKOBAUDAT, which are mapped onto each country's specific district heating mix. Because the energy transition moves at different speeds across Europe, the module leverages data from the HRE5 models to map the exact composition of each country's district heating mix at key milestone years – 2030, 2040 and 2050.

Following the HRE5 Recommended supply mix for renewable sources, the module prioritizes the integration of waste and renewable heat sources based on temperature and spatial proximity. However, as these sources cannot cover the demand, the remaining gap is then covered by a projected EU- average mix of largely large-scale heat pumps but also combined heat and power plants (CHP) and fuel boilers, as shown in Figure 19 .

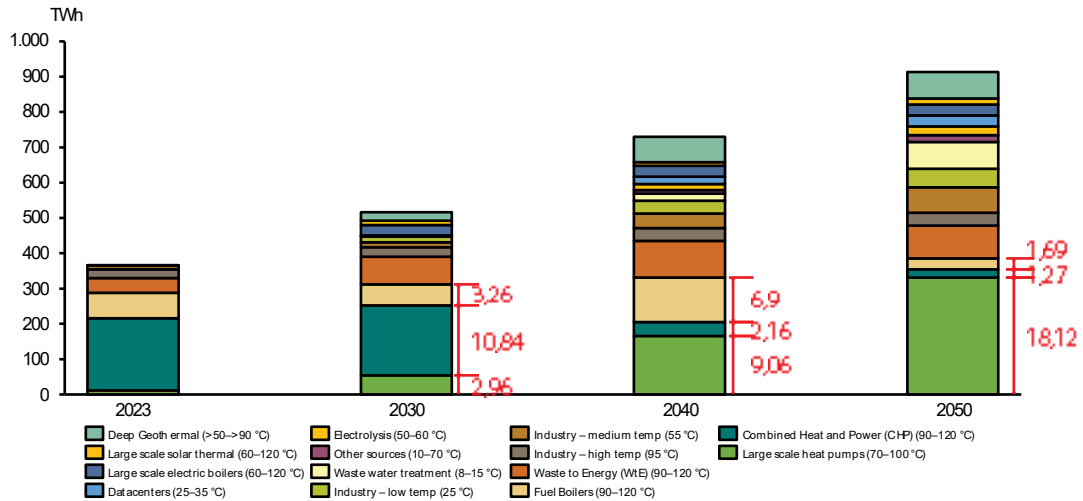


Figure 19. Projected district heating supply mix, EU average (Mathiesen, et al., 2026)

Final emission factor for district heating of a certain country, in kg CO<sub>2</sub>eq/kWh, can be described with the following formula:

$$GWP_{energy} = \sum_{i=starting\ year}^{i+49} R_{source\ in\ year\ i} \times GWP_{source\ in\ year\ i} \times E_{annual}$$

where

$GWP_{energy}$  are GWP emissions from energy use

$R_{source}$  is the specific source ratio in the district heating mix

$GWP_{source}$  is GWP emission factor for the specific source mapped from ÖKOBAUDAT

$E_{annual}$  is energy use per year

It is important to note the difference between EU Reference Scenario (used for country-specific electricity mixes) and the HRE5 scenarios when it comes to chosen time periods in the respective projections. EU Reference Scenario uses 5-year spans, while HRE5 uses 10-year spans. Thus, to align the timespans of the two projections, linear interpolation was used to fill the gaps in the HRE5 projection. As both sources define emission factors until 2050, the factors are held constant after that point.

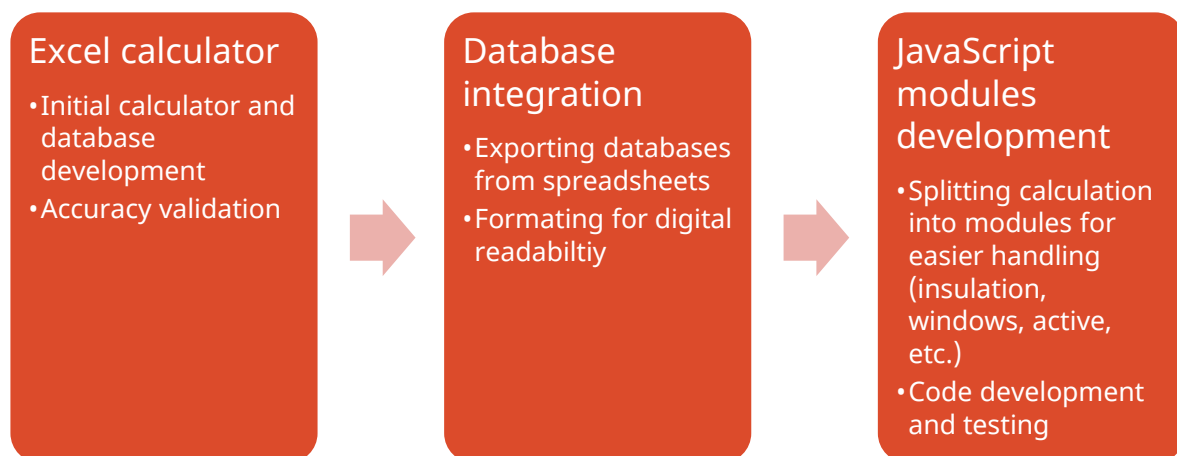
Furthermore, while some waste energy sources could be accounted as carbon free as previously described, some of them must be upgraded with heat pumps as the waste heat is not at a sufficient temperature. Thus, the code divides the interpolated grid electricity emission factor by the projected COP, 4.2 in 2030, transitioning linearly to 5.5 in 2050 (Mathiesen, et al., 2026), to calculate the operational emissions of the large-scale heat pumps.

The database covering emission factors for district heating, is available in [Annex 12.9](#).

## 7.2. Development

This chapter outlines the software engineering workflow, the transition from Excel-locked formulas to stateless scripts, and the modular architecture built within Drupal.

The primary engineering hurdle of the transition lay in refactoring the multi-layered databases and formulas, originally compiled in Excel workbooks, into structured, searchable, and web-native data formats that are deployed in Drupal. This chapter lays out the development concept and efforts until the point of writing of this report, and changes to the code will naturally happen, but the mathematical principles defined below should remain in large.



### 7.2.1. Deconstructing the spreadsheet

First drafts and versions of the calculators were developed in Excel spreadsheets, to allow for quick iterations, easier collaboration, and early tests of mathematical accuracy. The approach was simple, with the first sheet doing the calculation, and databases organized in the following sheets.

In the spreadsheet prototype, on the example of insulation solutions, they were separated across multiple categories (e.g., "IWI", "EWI", "RI", "BFI"), with formulas retrieving data using cross-sheet cell coordinates. This data could be reused in the web-based version of the toolkit, where each row represents a solution, identified with a specific code (i.e. IWI4, EWI2, etc.).

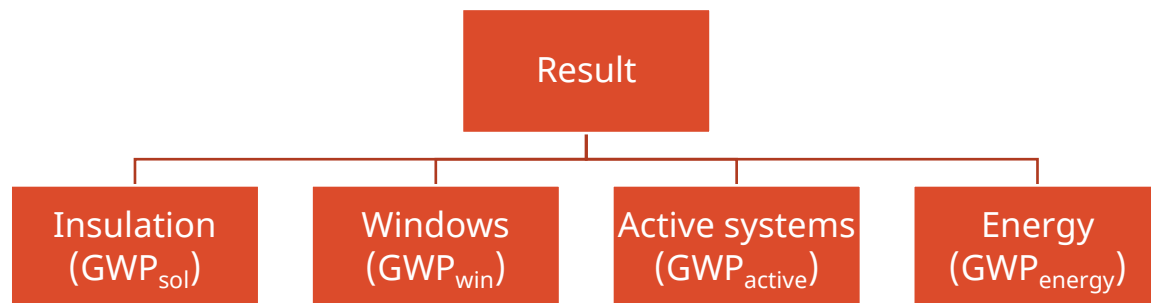
All the other inputs that are necessary for the calculation, like solution selection, thickness, application area, target country etc. are collected or calculated in the previous steps of the tool, namely Baseline Assessment, and Solution Selector. They are maintained inside a shared global memory, each as its own variable. For the sake of an example, when user enters the country where the building is, that would be saved as `v.country`. From that point on, that information is available for any other tool that might need it. This approach was utilized with insulation solutions and window solutions.

To test different approaches of the Drupal platform, where FuturHist toolkit is deployed, the database for the LCA tool in case of active solutions was changed. Instead of building a single place where the solution where gathered, necessary values were added to each solution as a direct attribute.

Once the values necessary for the calculation were “living” in the toolkit, the calculation can be executed.

## 7.2.2. Calculation modules

The JavaScript code for the LCA tool was developed in discrete modules, as seen in the chart below. The codes will be shared as an open-source repository in the upcoming period, along with the final release of the toolkit.



All the modules share certain features. For example, they all collect which solution is to be evaluated from the user’s selection, using variables such as `v.iwi` which stores exactly that in case of interior wall insulation. Furthermore, they all use several “dummy” inputs, that are implemented as a replacement from tools that are not yet deployed in this version of the toolkit. Such is the case with application area for insulations, `v.baseline_kwh` for example, which is calculated by PBE.

Once the calculation is done, they all pass the results back to the shared global memory, so it can be used for a Result summarization, or for use in other tools.

### 7.2.2.1. Insulation solutions LCA module

Calculation modules in Drupal can be set up in several different ways, which will each be described in the following chapters. In this module, to implement the multi-layered assembly (Substructure, Insulation, and Finish), Excel solution database sheet was uploaded directly as an attachment to be operationalized by the code. At runtime, the platform parses this as a CSV (comma-separated-values) and loads its content into memory as the `rows` object, making it instantly searchable by the calculation engine.

The workflow of the module can be described through the following steps:

1. The script queries user selections from the global memory state – solutions, thickness, country, etc.
2. As some of the insulation solutions have variable thicknesses, the code checks the database for the identifiers `ins_var`, `ins_min` and `ins_max`. If the user has input thickness outside of the given range, it is automatically bound to the closest valid limit. The code also checks the database for a `sub_var` identifier, to scale the substructure emissions if necessary, using the same thickness as for the insulation. As finishes usually come in a fixed thickness, they are not factored for variable thickness.
3. Materials degrade and must be replaced over the 50-year Reference Study Period (RSP). The script solves this by using the Reference Service Life (RSL) found in the database, `sub_lifespan`, `ins_lifespan` and `fin_lifespan`, to find the number of replacements needed over the RSP, rounding to the next integer number. This ensures that the emissions associated with full manufacturing, delivery, and end-of-life disposal cycles are accurately captured.
4. Finally, the module sums the manufacturing (A1–A3) and disposal (C3–C4) GWP emissions for each of the three sub-layers (Substructure, Insulation, and Finish), multiplies them by their calculated lifecycle replacement factors, and multiplies the final unified sum by the applied wall surface area `v.wall_area`, which is approximated from collected inputs in the Baseline Assessment (net floor area, number of floors).

#### 7.2.2.2. Window solutions LCA module

The window solutions module uses the same architecture as the previous one, but this time with some adaptations. The module separates each window solution into three distinct physical components: Glazing, Frame, and Coats/Sealings.

The workflow of the module can be described through the following steps:

1. Window solutions are manufactured and installed as complete, fixed systems. Hence, there is no need for identifiers to determine minimum and maximum thickness, only for the factors that scale GWP datapoints to one square meter of the solution – `gla_factor`, `frame_factor` and `cs_factor`.
2. In a standard window system, different components degrade at different rates, hence the script runs the replacement loop for each of the three components independently, using `gla_life`, `frame_life` and `cs_life` identifiers. Again, the rounding is made to the next integer number.
3. Similar to the previous module, the final step is the summation of GWP emissions for each of the three sub-layers (Glazing, Frame, and Coating/Sealings), multiplies them by their calculated lifecycle replacement factors, and multiplies the final unified sum by the applied window surface area `v.window_area`, which is currently a “dummy” input.

### 7.2.2.3. Active systems LCA module

The active systems module is designed to evaluate equipment (such as heat pumps, biomass boilers, RES systems, ventilation units, etc.) while excluding distribution lines, ductwork, and electrical wiring. It represents a departure from the tabular structure of the passive envelope (insulation and windows) calculations, as the database for active systems is integrated directly into the Drupal platform as field attributes individual solution entities.

The workflow of the module can be described through the following steps:

1. The module pulls the needed attributes from the solutions, in form of the variables stating the total GWP (including A1-A3, C3 and C4) per kW of power - `LCA_active`; and a reference service life - `RSL_active`.
2. Active equipment emissions scale by the system's power capacity (kW). Currently, the active solutions calculator uses an estimated power density ("dummy" input) of 80 W/m<sup>2</sup> of floor area to approximate the equipment capacity. Once PBE is operational within the tool, this number will be replaced with an accurate reading from the energy simulation outputs. This is the first multiplier to calculate carbon emissions from the active system.
3. Second, and the final, factor to be applied is the replacement one. Like previous tools, the code reads the reference service life from the global memory and the variable `RSL_active` and calculates the number of replacements.
4. Final multiplication of the `LCA_active` and the two described factors provide the result for this module.

### 7.2.2.4. Energy use LCA module

Evaluating the operational energy phase (Module B6) requires mapping distinct carbon emission factors to the different grids, across European countries over a 50-year horizon. In this case, databases used to map these emission factors were hardcoded into JavaScript modules as libraries. This choice guarantees zero database retrieval latency and ensures that the complex multi-year matrix calculations execute instantly on the client side.

The module calculates the results using the following steps:

1. The carbon intensity of different sources is determined in two ways, either using a fixed carbon emissions factor (gas and biomass), or using a sourced and/or calculated carbon emissions factor (electricity and district heating). In the latter, linear interpolation is used to calculate carbon emission factors outside of the pre-defined 5-year or 10-year intervals.
2. As the emission factors are expressed in kg CO<sub>2</sub> eq./kWh, the result is calculated by simply multiplying with the annual energy use. In case of projected sources that are done for each year (as the carbon emissions are decreasing gradually), and in case of fixed

emission factor sources it can be done by multiplying with reference study period which is 50 years.

#### 7.2.2.5. LCA result module

The LCA Result Module is the compiler of the calculator. It does not perform primary calculations of its own; instead, its sole function is to pull the carbon outputs from the other four modules, compare the ex-ante and ex-post balances using the formula described in chapter 7.1.2.1, and format them for the user interface of the toolkit.

The module does so in following steps:

1. The code pulls the results from each module, who are stored in the global memory as new variables, for example `iwi_carbon`, `ri_carbon`, `op_baseline`, `op_improved`, etc.
2. It executes the formula for the final KPI result – reduction of GWP emissions expressed in percentage of the baseline.

## 7.3. Testing

A significant portion of the software development lifecycle was dedicated to verifying that the JavaScript calculation engine achieved exact mathematical alignment with the original Excel reference spreadsheets.

During this testing, several important outcomes can be highlighted:

- The mathematical accuracy of results of the modules is not hard to achieve, due to the use of simple methods and a clear scope of the calculation. The challenging part is the correct flow of inputs between different sections of the toolkit.
- Focus on single “helper” features is important. For example:
  - Allowing for automatic bounding to defined thickness ranges.
  - Ensuring that the number of replacements is an integer number.
  - Ensuring that the differences in code inputs (`iwi4` vs. `IWI4`) do not result in calculation failures.

Once the accuracy of the JavaScript code was validated, the development continued exclusively in the web-environment, as the accuracy could be easily checked with on-the-fly calculations of specific solutions, which were in some cases possible with simply “by-hand” methods.

## 7.4. Results and discussion

### 7.4.1. Main outcome and KPI alignment

The successful deployment of this computational engine directly operationalizes the environmental performance metrics defined under the "Environmental Values" dimension of the FuturHist Integrated Planning Toolkit. Specifically, the tool aligns with the primary Key Performance Indicators (KPIs) outlined in deliverable D1.6 'Assessment categories and KPIs: a multidimensional approach to performance assessment':

- **Operational GHG Emissions (kg CO<sub>2</sub> eq./kWh):** By consuming dynamic hourly thermodynamic outputs (B6 phase) and modeling country-specific grid and district heating decarbonization curves over 50 years, the tool provides a highly realistic, year-by-year operational carbon trajectory.
- **Embodied Carbon Emissions (kg CO<sub>2</sub> eq./kWh):** The calculator accurately measures the upfront and lifecycle replacement impacts (phases A1-A3, B4, C3, and C4) of all passive insulation assemblies, window solutions, and active equipment units.

### 7.4.2. Tool maturity and upcoming development milestones

Currently, the tool successfully pulls the necessary information from different sources within the toolkit, calculates and presents the results. The calculation is completely detached from the user front-end interface, meaning that the graphical identity of the tool can be developed without affecting the underlying tools.

Furthermore, due to modular build of the calculator, there is an opportunity to provide a more detailed insight to the user, that goes beyond required KPIs – dedicated embedded and operational carbon breakdown, graphical comparisons between two scenarios, etc.

In collaboration with FuturHist partners, the plans for development and improvements of this tool are (and not limited to):

- **Populating the solution databases**
  - Even though the LCA solution database is the one with the highest level of completion and the required amount of solutions for testing is satisfied, some work is still required to complete the database, mainly with high-end and non-conventional solutions such as aerogel insulations, for example.

- **Complete integration with pyBuildingEnergy**

- As mentioned, active HVAC embodied calculations rely on a static estimation of approximate equipment size, using nominal power as a proxy. The development of PBE integration will aim to replace this proxy with a calculated required peak power from energy simulation of the scenarios.

- **Selecting multiple active solutions**

- Because individual solutions from the database often only address one or two functions (for example, a system designed specifically for heating and domestic hot water but lacking cooling or ventilation capabilities), users must select multiple active solutions. A critical roadmap milestone is enabling the calculator to compile, run, and scale carbon replacement rates for multiple combined active solutions simultaneously.

## 8. Economy (LCC)

### 8.1. Concept and methodology

#### 8.1.1. Rationale for the Adoption of the LCC Tool

Within the multidimensional evaluation framework of the FuturHist Integrated Planning Toolkit, Life Cycle Costing (LCC) serves as the primary financial indicator under the "Economic Values" dimension. This approach contextualizes upfront capital expenditures (CAPEX) for building materials and active installations against long-term operational expenditures (OPEX) over a 50-year timeline.

Added to the same reasons listed for developing a dedicated LCA tool, additional obstacle in the case of LCC was challenging integration of existing tools into the setup of FuturHist toolkit that is running on Drupal. Again, the priority was to adapt the tool to the specific typology-solution driven approach FuturHist has, so a custom tool for this KPI is being developed as well. However, one of the explored tools in deliverable D1.4 'Selection of tools: a review of guidelines and tools for energy retrofits in historic buildings' (Hupkes, et al., 2025) were used to test the accuracy.

#### 8.1.2. Method and Required Inputs

##### 8.1.2.1. Calculation Method

The core financial engine follows the relevant methods from standards EN 15643 (European Committee for Standardization (CEN), 2021) and ISO 15686-5 (International Organization for Standardization, 2017). However, there is an important difference compared to the standard approach – FuturHist LCC tool works with gross prices, rather than with net prices. This decision was made because the datasets used for adjusting the prices across Europe reflect the end price for the user (including taxes, margins, etc.) - so-called purchasers' price (European Commission, Eurostat, 2026), but also in an effort to provide a more realistic estimate on possible saving, as gross amounts answer more to what the user can see on the bill. The model tracks expenditures by compounding initial investments, discounted periodic replacements, ongoing operational servicing, and lifecycle utility costs.

The financial tool first establishes a baseline expenditure curve (ex-ante scenario) for energy use over 50 years, using consumption metrics supplied by the PBE simulation engine. It then runs a comparative evaluation for an ex-post scenario. This post-intervention model aggregates the capital investment, maintenance, and replacement costs of the chosen building envelope and active system improvements, then adds the discounted post-intervention energy costs over the identical 50-year calculation framework.

The primary financial metric delivered is the net difference in global lifetime costs, expressed as a percentage variation against the un-renovated state, defined by the following formula:

$$LCC_{dif} = \frac{LCC_{energy,baseline} - \sum(LCC_{sol} \times A_{sol}) + (LCC_{win} \times A_{win}) + \sum LCC_{active}(P) + LCC_{energy,improved}}{LCC_{energy,baseline}} \times 100\%$$

where

|                         |                                                                                             |
|-------------------------|---------------------------------------------------------------------------------------------|
| $LCC_{dif}$             | is the percentage financial variance between the ex-ante and ex-post whole-life costs       |
| $LCC_{sol}$             | represents the lifecycle cost rate for an insulation intervention                           |
| $A_{sol}$               | is applied area for insulation solutions                                                    |
| $LCC_{win}$             | stands for the total lifecycle cost for a window solution                                   |
| $A_{win}$               | is applied area for window solutions                                                        |
| $LCC_{active}(P)$       | is the lifecycle cost for active system equipment, scaled per nominal power of the solution |
| $LCC_{energy,improved}$ | is the cumulative present value of energy bills after the renovations                       |
| $LCC_{energy,baseline}$ | is the cumulative present value of baseline energy bills                                    |

### Databases – Sourcing, Formulation, and Mathematical Principles

The backbone of common LCC practice is an extensive reference construction and energy cost database, which usually breaks costs down to material acquisition and labor-hours needed for installation.

While it is rather easy to access statistics that track different energy source prices, the same cannot be said for construction costs, which need to cover passive and active solutions in the context of FuturHist toolkit. These databases are usually charged for and are not available to a casual user. Hence, the collaboration was agreed between FuturHist and Molio (Molio, 2026), who is the provider of market prices for the widest range of construction works in Denmark, and covers a big majority of solutions present in FuturHist. Their platform Priskalk (Molio, 2026), was the source for the material and labor prices covering the solutions. Even though the exact prices used may not be shared openly, this report will describe the exact calculation procedures used in the tools, for the sake of transparency and replicability.

As the prices from Priskalk reflect Danish market prices, it was necessary to adjust them to markets across Europe. Eurostat tracks price indices across Europe in different industries, among them construction industry as well (European Commission, Eurostat, 2026). This database was

used to form a simple factor, anchored to Denmark, to calculate the price in other countries. As the Eurostat database is using Euro (EUR), currency exchange rate to Danish Crown (DKK) of 7,45 was used, which is an average across the past ten years.

Using trial access to other similar platform in Europe, namely German BKI Kostenplaner (Baukosteninformationszentrum Deutscher Architektenkammern (BKI), 2026), random comparisons were made and the variance of the results were below 30%, which was satisfactory considering the early-stage nature of the tool, as well as the differences in pricing definitions between the two catalogues.

Discount rates for FuturHist LCC tool are set at 3% annually across all solution categories and energy, which is a recommended standard for long-term LCC studies (Dodd, et al., 2021). This could, of course, be subject to change, depending on findings in future developments.

In the following chapters, developed databases will be described in detail.

### LCC Insulation Solutions Database

For passive insulation solutions, in collaboration with FuturHist partners responsible for passive solutions, typical technical build-ups were defined, and matching material and labor cost rates from Molio Priskalk were attached to each constituent layer. The build-up is split into three components - substructure, insulation, and finish materials. Following this data mapping, functional unit costs are factored so that the base rates reflect a single square meter of fitted system, accounting for variable thicknesses where adjustments are possible.

The lifecycle cost contribution of each part of the buildup can be described with the following formula, on an example for a substructure component:

$$LCC_{sub} = f_{sub} \times (C_{acq,sub} + \sum_{i=1}^{50} \frac{C_{acq,sub} \times r_{maint}}{(1 + r_{disc})^i} + \sum_{j \in R_{sub}} \frac{C_{acq,sub} \times (1 + r_{EoL})}{(1 + r_{disc})^j})$$

where

|               |                                                                                                                                                            |
|---------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $LCC_{sub}$   | is the cumulative net present expenditure calculated for the substructure component over the study period of 50 years                                      |
| $f_{sub}$     | is scaling factor for converting database unit to a single square meter (or scaling linearly per millimeter of thickness for variable thickness solutions) |
| $C_{acq,sub}$ | is the substructure acquisition cost, for material supply and initial installation labor-hours                                                             |
| $r_{maint}$   | is the maintenance rate of the acquisition cost [%]                                                                                                        |

|            |                                                                      |
|------------|----------------------------------------------------------------------|
| $r_{disc}$ | is the discount rate for the LCC study                               |
| $R_{sub}$  | is the array of years in which the replacement happens (RSL expires) |
| $r_{EoL}$  | is the disposal (End of Life) rate of the acquisition cost [%]       |

Described variables are a part of the insulation solution database. The result of a solution is a summary of these for all three parts of the build-up:

$$LCC_{sol} = LCC_{sub} + LCC_{ins} + LCC_{fin}$$

where

|             |                                             |
|-------------|---------------------------------------------|
| $LCC_{sol}$ | are life cycle costs for the given solution |
| $LCC_{sub}$ | are life cycle costs for substructure       |
| $LCC_{ins}$ | are life cycle costs for insulation         |
| $LCC_{fin}$ | are life cycle costs for finish             |

### LCC Window Solutions Database

Mirroring the passive envelope methodology, window configurations are tracked across three separate cost components: Glazing, Framing, and Coats/Sealants. Unlike insulation assemblies, window products are logged as fixed, factory-assembled packages without variable thicknesses. The primary database scaling factor focuses strictly on converting costs into standardized rates per square meter of window area.

The lifecycle cost contribution of each part of the window can be described with the following formula, on an example for a framing component:

$$LCC_{fra} = f_{fra} \times (C_{acq,fra} + \sum_{i=1}^{50} \frac{C_{acq,fra} \times r_{maint}}{(1 + r_{disc})^i} + \sum_{j \in R_{fra}} \frac{C_{acq,fra} \times (1 + r_{EoL})}{(1 + r_{disc})^j})$$

where

|               |                                                                                                                |
|---------------|----------------------------------------------------------------------------------------------------------------|
| $LCC_{fra}$   | is the cumulative net present expenditure calculated for the frame component over the study period of 50 years |
| $f_{fra}$     | is scaling factor for converting database unit to a single square meter of window area                         |
| $C_{acq,fra}$ | is the frame acquisition cost, for material supply and initial installation labor-hours                        |

|             |                                                                      |
|-------------|----------------------------------------------------------------------|
| $r_{maint}$ | is the maintenance rate of the acquisition cost [%]                  |
| $r_{disc}$  | is the discount rate for the LCC study                               |
| $R_{fra}$   | is the array of years in which the replacement happens (RSL expires) |
| $r_{EoL}$   | is the disposal (End of Life) rate of the acquisition cost [%]       |

Described variables are a part of the insulation solution database. The result of a solution is a summary of these for all three parts of the build-up:

$$LCC_{win} = LCC_{gla} + LCC_{fra} + LCC_{cs}$$

where

|             |                                                    |
|-------------|----------------------------------------------------|
| $LCC_{win}$ | are life cycle costs for the given window solution |
| $LCC_{fra}$ | are life cycle costs for frame                     |
| $LCC_{gla}$ | are life cycle costs for glazing                   |
| $LCC_{cs}$  | are life cycle costs for coatings/sealings         |

### LCC active solutions database

Opposite to other solutions in FuturHist, active solutions are not split up into components. The boundaries of the evaluation for active solutions are limited to equipment, such as central heat pumps, district heating substations, biomass boilers, renewable energy systems (RES), etc. It omits distribution networks like ductwork, wiring, and radiator units, as extracting these layouts requires detailed system designs that are unavailable during the early stages of the project.

Solutions in the database are scaled based on nominal power, as the system size affects the pricing. However, that ratio is not linear, as early tests and comparisons in Molio Prisdata showed. The price in this case follows economies of scale, meaning that the price per unit of power decreases as the system grows in power (Chilton, 1950), with crucial inputs being reference power markings from the price catalogues, to determine cost exponents.

The lifecycle expenditure model for active solution is defined as follows:

$$LCC_{active} = C_{acq,active}(P) + \sum_{i=1}^{50} \frac{C_{acq,active}(P) \times r_{maint}}{(1 + r_{disc})^i} + \sum_{j \in R_{active}} \frac{C_{acq,active}(P) \times (1 + r_{EoL})}{(1 + r_{disc})^j}$$

$$C_{acq,active}(P) = \begin{cases} C_{acq,active,min} \times \left(\frac{P}{P_{min}}\right)^{\beta_{low}} & \text{for } P \leq P_{min} \\ C_{acq,active,max} \times \left(\frac{P}{P_{max}}\right)^{\beta_{high}} & \text{for } P > P_{max} \end{cases}$$

where

|                   |                                                                                                                                                          |
|-------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| $LCC_{active}(P)$ | is the cumulative net present expenditure calculated for the active solution over the study period of 50 years                                           |
| $C_{acq,active}$  | is the acquisition cost, for material supply and initial installation labor-hours                                                                        |
| $r_{maint}$       | is the maintenance rate of the acquisition cost [%]                                                                                                      |
| $r_{disc}$        | is the discount rate for the LCC study                                                                                                                   |
| $R_{active}$      | is the array of years in which the replacement happens (RSL expires)                                                                                     |
| $r_{EoL}$         | is the disposal (End of Life) rate of the acquisition cost [%]                                                                                           |
| $P$               | is the nominal power of the active solution                                                                                                              |
| $P_{min}$         | is the minimum power of the reference active solution in the source database (Molio)                                                                     |
| $P_{max}$         | is the max power of the reference active solution in the source database (Molio), used as a base power for the higher scaling tier and different $\beta$ |
| $\beta_{low}$     | is the non-linear cost-capacity exponent governing the lower scaling tier ( $P < P_{max}$ )                                                              |
| $\beta_{high}$    | is the non-linear cost-capacity exponent governing the higher scaling tier ( $P \geq P_{max}$ )                                                          |

### LCC Energy Use Costs Database

To determine costs of energy use across the building's lifespan, it was necessary to map utility tariffs across Europe. The difference between two approaches can be observed:

- **Electricity and Gas:** Base tariffs were sourced using Eurostat datasets on gross electricity prices for households (European Commission, Eurostat, 2026), and non-households (European Commission, Eurostat, 2026), and gross gas prices for households (European Commission, Eurostat, 2026), and non-households (European Commission, Eurostat, 2026). Most recent prices available were used.
- **District Heating:** As there is no single statistics database where district heating prices across Europe are collected, this database included a lot of manual research and logging. Priority was naturally given to the tracked prices from official databases and/or providers,

ideally as gross price per kWh. When the available source databases were allowing, weighted average was calculated based on energy consumption.

In case of a few countries, the available source databases were tracking net prices, which was then adjusted by applying the tax rates for district heating and cooling (supply\_heating) from the EU Taxes in Europe Database (European Commission, 2026).

After exhausting the available databases, there was still countries without mapped district heating pricing, and as the pricing of heat provided this is usually strategical, meaning it is formed to be competitive with gas (some countries even attach official pricing rules to the market price of gas – Netherlands (Autoriteit Consument en Markt, 2025) for example), it is decided that the missing datapoints in this database will be mapped as 90% of the average gas price in the particular country.

This, and all the other databases, will undergo possible adjustments and expansions when the toolkit becomes available to a wider audience (internally first, followed by open access to everyone).

The databases are available as [Annex 12.10.](#), [Annex 12.11.](#), [Annex 12.12.](#), and [Annex 12.13.](#)

## 8.2. Development

The development of the LCC tool can be described in two stages:

### 1. Simplified LCC tool

Early development efforts were focused on simplifying the LCC calculations. As can be seen in previous chapters, there are numerous variables and values that are necessary to calculate the LCC. Over several brainstorming sessions with academy partners from Aalborg University, it was discussed if reducing this need was doable and justifiable.

The leading concept was for the calculation to stay anchored in the acquisition price that can be referenced from Molio catalogue, but to calculate other phases (maintenance, replacement and disposal) using empirical factors for each phase, that would of course, differ across solution categories. The formulation would then be as follows:

$$LCC = C_{acq} + C_{acq} \times f_{maint} + C_{acq} \times f_{repl} + C_{acq} \times f_{EoL}$$

where

$C_{acq}$  is the acquisition price

$f_{maint}$  is the factor for determining maintenance price across life cycle

$f_{repl}$  is the factor for determining replacement price across life cycle

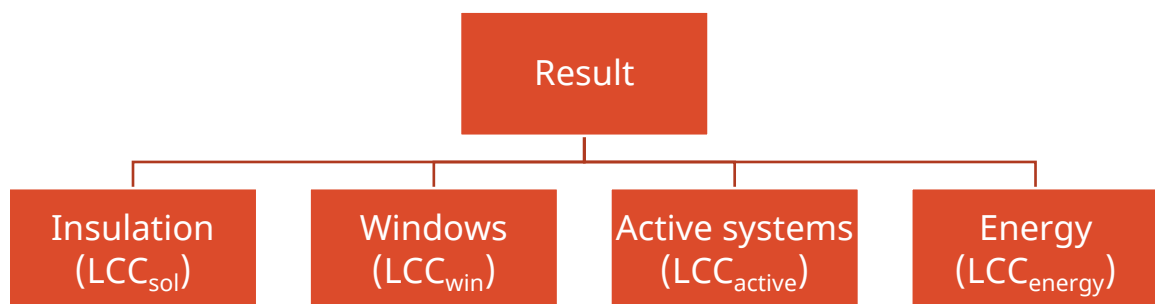
$f_{EoL}$  is the factor for determining disposal (End of Life) price across life cycle

Even though some academic sources could be found of for such ratios, where it is for example argued that there is an approximate 20-75-5 (%) breakdown across acquisition, use and disposal phase respectively (Gryzl, et al., 2017), it was important to notice that such ratios were defined on the level of the whole building, and were not fitting FuturHist level of detail targeted at building components.

The first drafts of the tool in Excel were trying to implement that logic, but without extensive previous work we could reference to, it was proving to be too extensive of a task for the project. The decision was made to resort to the standard method that was described in the [Chapter 8.1.2.](#), as the database structures and collected prices could be easily reused and the development did not have to restart.

## 2. Standard LCC

In the above-mentioned spreadsheet prototype for the simplified calculation, insulation options were categorized by solution types (e.g., "IWI", "EWI", "RI", "BFI"), with formulas retrieving material and labour rates, and with now added maintenance rates, lifespans, and any other needed variables via cell coordinates. The LCC tool utilizes the exact same decoupled architectural pattern as the LCA calculator. Every financial component module reads the active option identifiers from global memory and updates the centralized tracking state with its discounted cash flow results. Once the variables needed for each module are available, the calculation is executed.



The codes will be shared as an open-source repository in the upcoming period, along with the final release of the toolkit.

### 8.2.1. Calculation modules

#### 8.2.1.1. Insulation solutions LCC module

To implement the multi-layered cost assembly of the insulation options (Substructure, Insulation, and Finish), the original Excel database was used as an attachment within Drupal. At runtime, the

platform parses this file into a local memory, allowing the module's core evaluation loop to run queries directly against it.

The module operates as follows:

1. **Shared Filtering Mechanics:** The module utilizes the identical programmatic filtering mechanisms described in chapter 7 on LCA (e.g., retrieving codes from global memory, variable thickness bounding, and scaling substructures).
2. To account for material degradation over the 50-year life cycle, the script runs a temporal replacement loop. It matches individual component lifespans (`sub_lifespan`, `ins_lifespan`, `fin_lifespan`) against the study timeline to determine the precise future years when replacement occurs. The capital and deconstruction-premium costs of these future replacements are then individually discounted back to Present Value. As Futurhist LCC tool is focused on renovation of historical buildings, and the premise is that such buildings would not be demolished, the final disposal phase is omitted.
3. The module sums up the upfront installation capital, the discounted lifecycle maintenance costs (calculated dynamically as an indexed percentage of CAPEX per year), and the array of discounted replacement and disposal expenditures. The module multiplies this final per-unit cost rate by the total wall surface area placeholder (`v.wall_area`).

### 8.2.1.2. Window solutions LCC module

The window solutions module shares the same architecture as the insulation engine, adapted for fixed-assembly physical constraints. The module separates each window option into three components: Glazing, Frame, and Coats/Sealings.

The code runs the following steps:

1. As detailed in chapter 7 on LCA, windows are fixed systems. The module skips thickness bounding loops and directly retrieves fixed scaling constants to adjust base cost metrics to one square meter of window area.
2. Because window sub-assemblies degrade at different rates, the temporal replacement and maintenance loops run independently for each component using their respective lifespans (`gla_life`, `frame_life`, `cs_life`).
3. The final step sums the life-cycle expenditures computed across the glazing, frame, and seal components, ensuring all future material costs are discounted to NPV (applying the 125% factor to each future component swap), and multiplies the total cost by the window surface area (`v.window_area`), which currently utilizes a placeholder input.

### 8.2.1.3. Active systems LCC module

The active systems module evaluates the whole-life cost of primary thermal energy equipment. To correctly incorporate economies of scale identified during testing phases, the calculation structure abandons linear cost extension logic and processes costs using the piecewise non-linear cost-capacity function.

The module processes costs through the following steps:

1. The script queries the selected active system solution identifier against the dynamically loaded external spreadsheet rows, retrieving the baseline reference capacity (`base_kw`), the base baseline cost configuration (`base_price_dkk`), the technology pivot capacity limit (`pivot_kw`), the non-linear low tier sizing exponent (`beta_low`), the high tier sizing exponent (`beta_high`), and the unit service life (`lifespan`).
2. Active equipment expenditures scale non-linearly based on nominal power capacity (`kw_size`). Currently, the module applies an estimated power density placeholder of 80 W/m<sup>2</sup> of net floor area to establish initial capacity parameters. As PBE integration is explored further, this placeholder is planned to be updated with the exact sizing requirements calculated from peak thermal loads.
3. The runtime engine passes the capacity requirements into the segmented power-law function. If the power is lower than the upper limit, the low tier exponent (`beta_low`) is applied. Otherwise, the calculation is pivoted to the high tier exponent (`beta_high`) to prevent discrepancies. This scales the upfront capital costs (`capex`) and forms the baseline valuation from which annual maintenance fees are derived (calculated as an indexed percentage of the capacity-adjusted cost, discounted year-by-year to Present Value over the 50-year study timeline).
4. The script runs a replacement loop by matching the equipment service life against the 50-year calculation limit. For each equipment swap year identified, replacement is triggered, and discounted to Net Present Value, followed by a result calculation for the whole study period.

### 8.2.1.4. Energy use LCC module

Evaluating the operational expenditure phase requires mapping gross tariff registries and applying temporal discounting over a 50-year timeline. To eliminate data query latency, the country-specific pricing tables and lookup functions were compiled directly into client-side JavaScript libraries.

The module executes its calculations through the following steps:

1. The utility cost tracking handles energy carriers via database lookups, pulling country-specific gross tariffs (`base_unit_cost` or `imp_unit_cost`) for electricity, gas, and district heating.
2. To calculate the cumulative lifecycle energy cost, the script runs a 50-year temporal loop. For each year, it multiplies the constant real tariff by that year's simulated annual energy consumption (`base_kwh` or `imp_kwh`) from PBE. It then applies the compounding discount factor to convert that year's raw utility expenditure into its discounted Net Present Value. These discounted annual cash flows are then summed to yield the final lifecycle operational cost (`lcc_energy_base` or `lcc_energy_imp`).

#### 8.2.1.5. LCC result module

The LCC Result Module serves as the financial data compiler for the planning toolkit. It does not perform primary cost calculations; its sole function is to aggregate the net financial data from the four secondary modules, execute the global cost comparison formula described in Chapter [7.1.2.](#), and format the outputs for the user interface.

The module executes a rather simple sequence:

1. The script extracts the calculated whole-life costs from global memory variables (such as `lcc_total`, `lcc_total_active`, `lcc_energy_base`, and `lcc_energy_imp`).
2. It runs the global cost difference equation to compute the primary toolkit KPI: the total life-cycle financial savings or expenditure variations expressed as a percentage of the baseline asset state.

## 8.3. Testing

A key software quality assurance phase was executed to verify that the web-native, client-side JavaScript calculation engine achieved mathematical alignment with industry standard LCC software. To establish strict compliance with professional auditing guidelines, the development team conducted a formal validation process benchmarking the JavaScript engine directly against LCCbyg (4.0.52) (Haugbølle, et al., 2025) - Danish calculation platform developed by BUILD (Aalborg University).

### 8.3.1. Methodology and Parallel Benchmarking

The verification process evaluated the core deterministic cash flow algorithms across all functional layers of the tool - solutions implementation lifecycle costs and energy use lifecycle costs in baseline (ex-ante) and improved (ex-post) scenario. Standardized reference buildings and component build-ups were configured simultaneously in both the FuturHist web interface and the desktop LCCbyg environment using identical input parameters:

- **Temporal Framework:** A strict 50-year reference study period applying a standardized real annual discount rate of 3%.
- **Material & Equipment Parameters:** Identical initial capital expenditure rates (acquisition cost), reference service lives, annual maintenance percentages and end-of-life disposal ratios.

### 8.3.2. Verification Results and Parity Confirmation

The parallel simulations confirmed mathematical parity between the FuturHist JavaScript engine and LCCbyg calculations. The calculated NPV for tested solutions in LCCbyg aligned identically with results in the developed tool, confirming the correct handling of the following:

- Discount loops are running correctly across 50 years of study period, for both solution lifecycle costs, and energy lifecycle costs.
- Replacement loops are correctly compounding the costs of each Reference Service Life (RSL) cycle and discounting the replacement correctly.

## 8.4. Results and discussion

### 8.4.1. Main outcome and KPI alignment

The results of this tool are direct answers to the defined KPI in the "Economic Values" dimension of the FuturHist Integrated Planning Toolkit. By moving beyond short-term payback models and analysing costs over a 50-year study period, the tool helps users move towards a more in-depth decision-making. The KPIs outlined in deliverable D1.6 'Assessment categories and KPIs: a multidimensional approach to performance assessment' are:

- **Life cycle cost (LCC):** The main results of this KPI will be expressed as an achievement of the Target – "Reduction of 20 % compared to the baseline.", as expressed in the previous chapters.
- **Operational energy costs:** The tool calculates and handles energy costs across the study period and displays them to the user.

### 8.4.2. Tool Maturity and upcoming development milestones

The LCC tool currently runs with the set of required solutions for this deliverable and has achieved needed accuracy for the key results and KPIs. To advance the tool further, and prepare for the public release of the tool within the toolkit, the following features (not limited to this list) are planned for implementation:

- **pyBuildingEnergy integration improvements**

- Operational energy savings and active system sizing rely on standardized placeholder estimation (80 W/m<sup>2</sup> peak heat demand). Upon integrating the simulation engine into the toolkit, the LCC tool is empowered with a precise energy demands from the simulation, that are more fitting to the analysed building.

- **Expansion of European Price factoring and Fuel Registries**

- Currently, factoring Danish prices to the rest of the Europe works based on Eurostat datasets, which are lacking UK in their entries. To provide estimates for cases in UK, this data gap has to be filled with identical datapoint, or a new dataset must be found which allows for similar factoring based on the prices in construction industry.
- While electricity, natural gas, and district heating networks are mapped across most European economies, secondary renewable energy carriers, specifically biomass, wood pellets, and localized solar PV export tariffs, remain unmapped due to either lack, or decentralization (in case of UK), of statistical datasets. Currently, the tool is replacing some of these (biomass, oil) by tying them to known price of gas, but the efforts will be invested to incorporate regional pricing, potentially accompanied by custom user-override fields in the frontend interface.

## 9. Smart Readiness Indicator (SRI)

### 9.1. Concept and methodology

#### 9.1.1. Rationale for the Adoption of the SRI

The Smart Readiness Indicator (SRI) is a common European scheme introduced under the Energy Performance of Buildings Directive (EPBD) to evaluate the technological readiness of buildings to interact with their occupants and connected energy grids, and to operate efficiently (European Parliament and Council, 2024). The SRI has been formally recommended as a Key Performance Indicator (KPI) under the "Technical Compatibility" dimension (Leijonhufvud & Herrera-Avellanosa, 2025), and afterwards implemented into the multidimensional decision-making methodology of the FuturHist Integrated Planning Toolkit (Sand, et al., 2026). The target of the mentioned KPI was defined as a final score, rather than a comparison with the baseline scenario (as is the case with energy use, for example), hence it gave more value as a performance KPI, rather than technical compatibility criteria. The target was set to achieve at least an SRI score of Class C, or 65%.

The purpose of incorporating the SRI into the DSS is to measure the capacity of the suggested solutions to integrate smart-ready services, without compromising heritage significance. Moreover, although the SRI calculation can nowadays be performed using various tools, all these tools start from a standard calculation method defined by the EU Commission. The different tools can be more or less user-friendly but, in all cases, they require answering a notable number of questions, selecting the most appropriate answer from a list, and, in the case a specific technical domain (see below for the technical domains identification) is not present, this needs to be identified at the beginning of the evaluation. To simplify the process, maintaining the validity of the assessment, it has been decided in the redeveloped tool not to consider some technical domains a priori, as these are not relevant in the considered context of solutions included in FuturHist. More specifically, the Lighting, Dynamic Building Envelope, Electric Vehicle Charging and Electricity technical domains (see them and the entire list in section 9.1.2) are not considered. This results in a simplified and faster SRI assessment for the assessor, maintaining the original calculation method and, therefore, with the possibility to compare the results obtained using the FuturHist toolkit with the same results obtained from other tools.

## 9.1.2. SRI Method and Input/Output Parameters

### 9.1.2.1. Method

The calculation methodology is fundamentally based on the assessment of the "smart-ready services" that are either present or planned within a building. These services are defined across nine technical domains (European Parliament and Council, 2024):

1. Heating
2. Domestic Hot Water (DHW)
3. Cooling
4. Ventilation
5. Lighting
6. Dynamic building envelope
7. Electricity
8. Electric vehicle charging
9. Monitoring & Control

Services within these technical domains are evaluated against seven specific impact criteria (European Parliament and Council, 2024):

1. Energy efficiency
2. Energy flexibility and storage
3. Comfort
4. Convenience
5. Health, well-being and accessibility
6. Maintenance and fault prediction
7. Information to occupants

Each service can be evaluated on these impact criteria, with a functionality level on a scale of 0-4(5). Higher functionality level answers to a "smarter" implementation of the given service, which in return results in benefits for both the building, energy grid, and the users.

Before executing the calculation, there is a “triage process”, which ensures that buildings are not penalized for lacking services that are irrelevant or inappropriate. For example, if the cooling system is not present in the building, nor mandated by building codes or other regulations, it is excluded from the calculation. Effectively, this removes the services from the calculation, preventing unfair decrease in the final score.

The calculation process determines an aggregated score, expressed as a percentage, which represents the ratio between the achieved SRI score and the theoretical SRI score that is possible in that case. Thereafter, these functionality levels are used to calculate the domain impact score, which is weighted in several steps, depending on the building type and the local climate.

Finally, these domain scores are aggregated into three pillars to calculate the final score with equal 1/3 weights for all three. The pillars are:

1. Energy performance and operation
2. Response to user needs
3. Energy demand flexibility

There are many tools that are operationalizing this method, answering many specific needs on the market. FuturHist toolkit used an EU Commission approved and validated Excel Spreadsheet (European Commission, 2024) as a baseline for (re)developing the tool for our specific needs, and for comparing the results to assure accuracy. The spreadsheet can be requested by filling in the linked [survey](#).

### 9.1.2.2. Input and parameters

To successfully make the SRI assessment, there are different inputs and fixed parameters that must be set.

Firstly, general information about the building is collected. The most important parameters are the building type and the geographical setting (country) which will determine the weights that will be applied later in the calculation.

Secondly, available and relevant technical domains must be defined, to avoid overestimating potential maximum SRI score, as described previously.

Thirdly, all the applicable services and their functional levels are to be defined, after which the results can be finally calculated.

To align with the approach adopted in the FuturHist toolkit, the procedures for collecting and defining input data and parameters were adjusted. These adjustments are described in the following chapter.

## 9.2. Development

### 9.2.1. Tool architecture and deployed technologies

The primary objective of (re)development was to transition the highly complex Excel spreadsheet of the official European Commission Assessment package into a web-native JavaScript code, which is simpler and allows a faster assessment. The final tool is built for deployment within a web platform where the whole FuturHist toolkit is built and deployed.

The code of the modules will be shared openly as an online repository in the upcoming period, and along with the final release of the toolkit. Modules work as follows:

#### 1. Solution data fetcher

The foundation of the SRI evaluation within the FuturHist toolkit relies on the comprehensive database of active retrofit solutions compiled during Work Package 3 (Muchorowska, et al., 2025), and further expanded to include SRI service functional levels during the development of this tool.

These active systems were systematically parametrised across technical and performance specifications into a “SRI solution database”, capturing functionalities such as building automation and control systems (BACS), monitoring setups, centralisation capabilities, etc. Within the context of the toolkit's methodology, these specific technological features function as the exact input variables required to define the functionality levels across the various SRI domains.

The sole task of this module was to extract these parameters from the database and make them available for the calculation module.

#### 2. Weighing Matrix

Based on user inputs that define the country of the building in question, as well as the building type – residential or non-residential, this module determines which weighing factors are to be sent to and used in the calculation module.

This module is introduced as an effort to ease the updating of the mentioned factors as the implementation of the SRI framework advances across EU. They are expected to change after the testing phase is done and reported to the European Commission, and the findings are implemented to improve the method (European Commission, n.d.).

#### 3. SRI calculation

The last module executes the calculation according to the official method (European Commission, 2020) and as described in the previous chapter.

## 9.3. Testing

Testing was conducted through version validation cycles. Specific test variants written in JavaScript were compared side to side with the EU spreadsheet to validate accuracy. When persistent margins of error were detected during early builds, cross-examination was expanded to trace and eliminate the source of error. It was an integral part of development process, as it provided a strong mechanism for better understanding of the calculation method and hence improvement of the code, as well as for testing accuracy.

Specifically, the goal of each test was to compare the following scores [%]:

- Final SRI
- Energy Efficiency
- Grid Flexibility and Storage
- Comfort
- Convenience
- Health and Wellbeing
- Maintenance and Fault Prediction
- Information to Occupants

For this phase, there were four active solutions used in the testing, as required by Grant Agreement, and as follows:

- Central heat generation system with boiler for biomass and ceiling heating
- Central heat generation system with external heat pump and floor heating
- Central heat generation system with gas boiler and wall heating
- Central heat generation system with heat pump and floor heating (with mechanical ventilation)

Solutions were tested individually in each test run.

## 9.4. Results and discussion

### 9.4.1. Main lessons

As previously described, the SRI method includes a triage process to fairly assess buildings based only on the services that are relevant. Through sparring sessions with FuturHist partners responsible for active solutions (WP3), it was decided that SRI in the context of FuturHist can only include technical domains that the solutions are addressing – Heating, Domestic Hot Water, Cooling, Ventilation, and Monitoring and Control.

Early versions of the code excluded the rest of the technical domains, but they failed to properly address non-present services within active technical domains, resulting in consistently lower SRI scores than the official SRI Calculation Spreadsheet was outputting. This was happening because certain solutions are not covering all the services within a single technical domain, and the code took that into account, but did not exclude the maximum number of points for that service out of the total SRI score calculation. This causes inflated maximum possible score and lowering achieved score.

Thus, a part of the third module was rewritten to match the triage rules of the SRI calculation spreadsheet, after which the results from the developed JavaScript code became consistently accurate across all four solutions used for testing of the tool.

#### Testing outcomes and alignment with FuturHist KPI for SRI

The primary outcome of the development and testing phase, a calculation engine that achieves mathematical parity with the EU v4.5 SRI Calculation Spreadsheet across all tested solutions, can be considered as achieved. Results of the comparative testing can be seen in Table 15. The successful deployment of this engine directly operationalizes the Smart Readiness KPI defined in deliverable D1.6 ‘Assessment categories and KPIs: a multidimensional approach to performance assessment’.

Table 15. Final accuracy testing results for SRI calculator, on an example of a residential building in Finland

| Solution                                                                   | Results from EU v4.5 SRI Calculation Spreadsheet | Results (re)developed from FuturHist SRI calculator |
|----------------------------------------------------------------------------|--------------------------------------------------|-----------------------------------------------------|
| Central heat generation system with boiler for biomass and ceiling heating | 24.0 %                                           | 24.0 %                                              |
| Central heat generation system with external heat pump and floor heating   | 30.9 %                                           | 30.8 %                                              |
| Central heat generation system with gas boiler and wall heating            | 25.9 %                                           | 25.9 %                                              |
| Central heat generation system with heat pump and floor heating            | 30.6 %                                           | 30.5 %                                              |

## 9.4.2. Tool maturity and upcoming development milestones

Currently, the tool operates as a fully functioning and independent calculation engine that is structurally separated from the visual user interface, meaning the mathematical logic is kept distinct from the web pages, questionnaires, and buttons that the user interacts with. While the user's answers are collected on the front-end interface, this information is packaged into a simple data string and sent to the calculator. This separation is highly beneficial, as it ensures that the website's design or question phrasing can be updated freely without risking any disruption or errors in the underlying calculation rules.

The tool is, as previously described, built in modules, easing future updates and feature implementation. In collaboration with FuturHist partners responsible for active solutions (WP3), the following is planned as a roadmap for the SRI tool:

- Finalization of the SRI solution database

The complete Active Solution Library in FuturHist has 47 solutions, all of which need to be mapped with relevant SRI service functionality level to complete the SRI solution database.

- Multiple active solutions

A fully functioning building must adequately cover various technical domains. Because individual solutions from the database often only address one or two of these functions (for example, a system designed specifically for heating and domestic hot water but lacking cooling or ventilation capabilities), users will necessarily have to select multiple active solutions to satisfy the building's overall demands. Now that the accuracy of the tool is ensured, one of the most important steps forward is enabling the user to cover domains that are relevant for the building in question.

# 10. Conclusions and Outlook

## 10.1. Overall outcome

The principal achievement of D4.2 is the translation of the FuturHist methodology from a conceptual framework into a set of operational decision-support resources. The report builds on the typologies, tool reviews, KPIs and multidimensional methodology developed in D1.2, D1.4, D1.6 and D4.1, respectively. Its purpose is therefore not simply to present individual calculators and guides, but to demonstrate how these foundations can be converted into tools that support early-stage decisions in actual renovation processes.

The selected tools deliberately require limited input and provide rapid, sufficiently robust results for users who cannot be expected to possess specialist knowledge in all the dimensions addressed by FuturHist. They are not intended to replace detailed heritage assessments, advanced simulations or professional design. Their role is to help users narrow the solution space, identify potential risks and compare plausible renovation scenarios before committing resources to detailed analysis.

## 10.2. Main outcomes and importance in the FuturHist context

### A coherent process for filtering and selecting retrofit solutions

A three-stage decision-tree process was developed to connect building typology, heritage vulnerability, technical compatibility and user priorities. Typology information first excludes evidently unsuitable measures and removes irrelevant questions. Building-specific conditions and user requirements then refine the selection. Finally, the remaining solutions can be ranked according to priorities such as cost, reversibility, embodied energy, service life and recyclability.

Testing with the four demonstrator contexts showed that the filtered lists retained the measures selected for the corresponding real renovation scenarios while reducing the broader lists of typology-compatible measures. The tests also led to improvements in the wording of questions, the distinction between filtering and ranking criteria, and the allocation of information to typology, building or user-preference levels.

**Importance in the FuturHist context:** This decision tree is the mechanism that turns the typology concept into practical decision support. Rather than merely describing recurring building characteristics, FuturHist uses typologies to reduce both the number of candidate solutions and the amount of information required from the user. It also provides the connecting

structure through which heritage and technical knowledge influence the scenarios subsequently assessed for energy, environmental and economic performance.

### Heritage significance made actionable without oversimplifying its role

The heritage work resulted in a simplified impact-assessment framework based on three types of intervention impact: material, visual and spatial. Expert-defined vulnerabilities of characteristic building elements are embedded at typology level and combined with the expected impacts of individual renovation measures. Building-specific questions allow the initial typology assessment to be refined where the actual building differs from the general typology.

The resulting logic distinguishes between solutions that are broadly acceptable, solutions requiring warnings or further investigation, and solutions that should normally be excluded. Testing across the first four typologies confirmed that the framework was suitable for its intended purpose, while also identifying necessary adjustments for specific features such as cavity walls, ceilings, façades and original glazing.

**Importance in the FuturHist context:** This is a distinctive contribution because heritage is not treated as a final qualitative check after technically attractive solutions have already been chosen. Instead, heritage considerations influence the first filtering of measures. At the same time, the method recognizes that typology-based guidance cannot replace an expert assessment of an individual building, its statutory protection or unusual features. The framework therefore makes heritage operational at an early stage while retaining a clear boundary between decision support and professional judgement.

### A progressive technical-compatibility pathway

Technical compatibility was addressed through three complementary levels:

- **Informing resources**, including guides for internal insulation, component integration, photovoltaics and heat pumps.
- **Decision-support resources**, including pre-calculated hygrothermal assessments, typology-specific junction compatibility and active-system feasibility checks.
- **Detailing resources**, including thermal-bridge examples and the HeatFlux Tool for analysing in-situ measurements.

The internal-insulation and component-integration guides translate complex knowledge from RIBuild and FuturHist WP2 into accessible, stepwise workflows. The component-integration work is particularly important because it moves the assessment beyond individual products to the junctions and interfaces where thermal bridges, air leakage, driving rain, rising damp, condensation and mould risks often arise.

The hygrothermal resource extends earlier RIBuild simulations to additional FuturHist constructions, materials, locations and future climates. Complex results are presented through a simplified assessment centered on mould risk, while uncertain configurations remain available for further project-specific investigation rather than being treated automatically as unsuitable.

Testing indicates that these resources are sufficiently mature for toolkit integration. The HeatFlux Tool reproduced manual calculations made according to ISO 9869-1, while the other resources were validated through expert review, consistency with their underlying research and initial implementation checks.

**Importance in the FuturHist context:** Together, these resources address a central risk of historic-building renovation: a solution may appear beneficial in isolation but fail when connected to existing materials, junctions, moisture conditions or services. The progressive structure also reflects the FuturHist philosophy. Users start with simple guidance and screening but can move towards more detailed evidence when uncertainty or risk warrants it.

### A workable early-stage energy engine

PyBuildingEnergy was selected because it is open source, based on European building-energy standards and less demanding than more detailed simulation platforms. Archetype input models were prepared for typologies represented by demonstrator cases, and baseline and ideal scenarios were compared with calculations undertaken in WP5.

The feasibility study showed that, with limited input, PBE generally identified energy-saving tendencies comparable to the more advanced tools used in WP5. Agreement was reasonably good for Spain, Poland and Sweden, while the Scottish ideal scenario showed a substantial discrepancy requiring further investigation. The report appropriately characterizes this as a feasibility test rather than a validation.

Current limitations include the treatment of domestic hot water, active-system efficiencies, adiabatic surfaces, complex orientations and sloping roofs. Consistent weather data must also be used between early-stage and detailed calculations.

**Importance in the FuturHist context:** PBE provides the quantitative link between selected measures and the subsequent environmental and financial calculations. Its value lies less in reproducing detailed simulations exactly and more in enabling consistent comparison of scenarios early enough to influence strategy. This is essential to the toolkit's ambition to combine ease of use with evidence-based decisions.

### Indoor environmental quality retained as a core consideration

The IEQ outcome is an educational guide rather than another calculator. It explains thermal comfort, overheating, humidity, mould, ventilation, carbon dioxide, particulate matter and volatile organic compounds in accessible language. It also helps users recognize when monitoring or specialist assessment is justified.

**Importance in the FuturHist context:** The guide prevents energy savings from becoming the sole definition of successful renovation. It supports a whole-building perspective in which fabric changes, ventilation, services and occupancy are considered together. This is particularly important in historic buildings, where improving airtightness or insulation can produce unintended effects on moisture, comfort and indoor air quality if interactions are overlooked.

### Operational LCA and LCC calculations

Dedicated web-based LCA and LCC tools were developed because conventional tools were too detailed and input-intensive for FuturHist's early-stage, typology-and-solution-based workflow.

The LCA tool compares baseline operational emissions with the combined embodied and operational emissions of an improved scenario over 50 years. It covers insulation, windows, major active equipment and operational energy, and uses country-specific projections for electricity and district heating. The calculation modules were successfully transferred from Excel prototypes into modular JavaScript components within the toolkit.

The LCC tool similarly compares baseline and improved scenarios over 50 years, including acquisition, maintenance, replacement and operational energy costs. Its calculation engine achieved mathematical parity with LCCbyg for the tested inputs.

**Importance in the FuturHist context:** These tools enable renovation packages to be judged on whole-life consequences rather than energy savings or initial investment alone. This is crucial because the environmentally or financially preferable intervention may not be the one with the greatest theoretical reduction in energy need. By connecting LCA and LCC to the same scenario used by the other modules, FuturHist supports genuinely multidimensional comparison rather than parallel, disconnected assessments.

### A simplified but methodologically consistent SRI tool

The official European SRI calculation was converted from a complex spreadsheet into a modular, web-native calculation engine. The assessment was tailored to the active-system domains relevant to FuturHist while retaining the official calculation logic and triage rules. Testing against the EU spreadsheet produced nearly identical results for all four tested active solutions.

**Importance in the FuturHist context:** The SRI module broadens the definition of future-proof renovation. It allows scenarios to be considered not only in terms of fabric, energy and carbon, but also in terms of their capacity to respond to users, building operation and energy systems.

## 10.3. Overall significance

Taken together, the outcomes show that FuturHist has progressed from defining a multidimensional methodology to demonstrating the technical feasibility of its main components. The report does not yet demonstrate a fully mature end-user platform. It does, however, establish that typology information, solution filtering, heritage impact, technical risks, energy calculations, IEQ guidance, LCA, LCC and smart readiness can be connected within one decision pathway.

The wider significance is that FuturHist offers an intermediate level between generic renovation guidance and project-specific expert design. This intermediate level is currently difficult to provide for historic buildings because decisions are distributed across different disciplines, tools and professional responsibilities. D4.2 shows how these perspectives can be coordinated early

enough to prevent unsuitable solutions, expose trade-offs and identify where more detailed investigation is necessary.

## 10.4. Next steps

The deliverable identifies several important activities for the coming phase:

**Toolkit integration.** The main priority is to complete the integration of all developed tools and guides into the digital FuturHist toolkit including typology selection, filtering, scenario definition and multidimensional assessment function as one continuous user journey. Further to evaluate the complete user workflow. Future testing will focus less on scientific validity and more on usability, clarity and user interaction with the toolkit.

**Complete and quality-assure the underlying datasets.** Expand hygrothermal coverage, component-integration examples, LCA solution data, LCC price coverage and the SRI mapping of active solutions.

**Finalise the energy-calculation implementation.** Resolve domestic hot water, active-system efficiency, adiabatic-surface and weather-data issues; and complete archetype models for typologies without demonstrator cases.

**Strengthen links between PBE, LCA and LCC.** Replace placeholder values for energy use and active-system capacity with outputs from the integrated energy model.

**Enable combinations of active systems.** Both LCA/LCC and SRI are intended to support realistic scenarios containing several systems covering heating, cooling, ventilation and domestic hot water.

**Maintain transparent boundaries around the toolkit.** The final user interface should state clearly when results are based on typology assumptions, when building-specific input has been used, and when heritage, hygrothermal, structural or systems expertise is still required.

The central next step is therefore not to add further independent tools, but to mature their interaction. The success of the FuturHist toolkit will depend on whether users can move transparently from typology and building information to a defensible renovation scenario, understand the trade-offs revealed by the different dimensions, and recognize when the early-stage assessment must be followed by specialist analysis.

## 10.5. Overall outlook

The deliverable shows that the fundamental components of the FuturHist toolkit have been selected, adapted and tested for accuracy to the possible extent. The next stage is therefore less about choosing methods and more about maturing, integrating and user-testing the complete platform in preparation for wider deployment and demonstration activities.

# 11. References

References used in chapter 6 can be found in annex 12.5.

## FuturHist deliverables

All FuturHist deliverables can be found in the « Resources » page of the project's website <https://futurhist.eu/resources/>. Additionally, and after approval by the European Commission, deliverables can be found in CORDIS (<https://cordis.europa.eu/project/id/101138562/results>) and Zenodo (<https://zenodo.org/communities/futurhist/>) repositories.

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## 12. Annexes

### 12.1. Internal insulation guide

Annex 12.1 presents the complete step-by-step guide. In the final version integrated in the toolkit, the guide will be formatted in line with the photovoltaic and heat pump guides to ensure consistent visual identity, graphic style, and layout across all FuturHist guidance resources.

INTERNAL INSULATION IN HISTORIC BUILDINGS

# Internal Insulation in Historic Buildings

*A Seven Step Guide for Architects and Consultants*

## **RIBuild decision workflow**

**Set goals → Know the building → Select systems → Evaluate  
performance**

Based on the results of the RIBuild research project

More information: [www.futurhist.eu](http://www.futurhist.eu) and [www.ribuild.eu](http://www.ribuild.eu)

INTERNAL INSULATION IN HISTORIC BUILDINGS

## About this guide

This short guide translates the RIBuild online guidelines into a compact step-by-step workflow. It is designed as a navigation aid rather than a replacement for the full RIBuild website: each step gives the essential task, a practical outcome, and direct links to the relevant RIBuild subsection.

Use it at the start of a project to structure discussions with clients, heritage authorities, consultants and contractors. For detailed explanations, examples, checklists, calculators and research background, follow the links provided in each step.

Direct links: [Home](#) | [Knowledge Base](#)

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Scope: internal thermal insulation of historic buildings, with attention to goals, building condition, moisture risks, system selection and energy/environmental/cost evaluation.

More information: [www.futurhist.eu](http://www.futurhist.eu) and [www.ribuild.eu](http://www.ribuild.eu)

INTERNAL INSULATION IN HISTORIC BUILDINGS

## Welcome!

Improving the energy performance of heritage buildings is not only about reducing heat losses. It is also about respecting significance, avoiding moisture-related damage and choosing measures that suit the specific building.

RIBuild provides online guidance and tools for deciding whether internal insulation is appropriate, what information is needed, which systems may be suitable, and how energy savings, environmental impact and life-cycle costs can be assessed.

After following these steps, the project team should have a clear overview of whether internal insulation is worth investigating further, which risks must be addressed, and which RIBuild pages should be consulted next.

**The process is iterative: if a later step reveals unacceptable risk or conflict with project goals, return to the relevant earlier step and revise the decision basis.**

More information: [www.futurhist.eu](http://www.futurhist.eu) and [www.ribuild.eu](http://www.ribuild.eu)

## INTERNAL INSULATION IN HISTORIC BUILDINGS

## Overview: planning internal insulation with RIBuild

Use the seven steps below as a quick route through the RIBuild material. Each step points to the corresponding RIBuild subsection so the full technical content remains one click away.

|                                                                                       |                                                                                          |                                                                                                |
|---------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| <b>1 Define what you want</b><br>Set goals and priorities before comparing solutions. | <b>2 Check what you have</b><br>Screen the building and identify warning signs.          | <b>3 Understand risks and constraints</b><br>Map exposure, sensitive parts and indoor climate. |
| <b>4 Collect evidence</b><br>Use measurements and checklists where needed.            | <b>5 Identify insulation options</b><br>Compare system families and application methods. | <b>6 Test performance</b><br>Use RIBuild tools to review hygrothermal and energy outputs.      |
| <b>7 Evaluate and decide</b><br>Compare energy, LCA/LCC and final project priorities. | <b>Tip</b><br>Follow the links in each step for the detailed RIBuild subsection.         |                                                                                                |

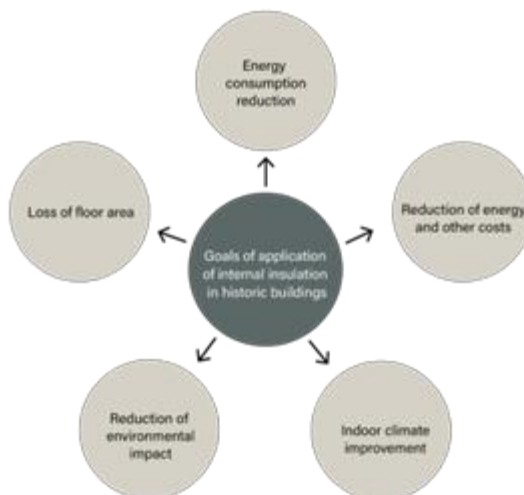
Direct links: [Set your Goal](#) | [Know your building](#) | [Insulation Systems](#) | [LCA/LCC](#)

More information: [www.futurhist.eu](http://www.futurhist.eu) and [www.ribuild.eu](http://www.ribuild.eu)

## INTERNAL INSULATION IN HISTORIC BUILDINGS

## 1 Define what you want

Clarify the project goal before selecting any insulation solution. Decide whether the priority is energy saving, reduced operating cost, indoor comfort, environmental impact, limited loss of floor area, or a balance between several objectives.



### Choose your goal category

|                                                                                                                              |                                                                                                                                        |                                                                                                                       |
|------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|
| <b>Energy</b><br>Reduce operational energy for heating, ventilating or cooling.<br><a href="#">Open RIBuild section</a>      | <b>Environment</b><br>Limit environmental impacts, from operational CO2 to life-cycle effects.<br><a href="#">Open RIBuild section</a> | <b>Cost</b><br>Consider investment, energy, maintenance and life-cycle costs.<br><a href="#">Open RIBuild section</a> |
| <b>Climate</b><br>Improve indoor thermal comfort and surface-temperature conditions.<br><a href="#">Open RIBuild section</a> | <b>Floor area</b><br>Minimise the usable floor-area lost to internal insulation thickness.<br><a href="#">Open RIBuild section</a>     | <b>Tip</b><br>You can combine more than one goal, but document the priority order before selecting systems.           |

### What to do

- ☐ Check regulatory and heritage constraints early.
- ☐ Agree measurable criteria with the client and key stakeholders.
- ☐ Record how different objectives should be weighted if trade-offs occur.

#### Outcome

By the end of this step, the project goals and priorities should be documented and shared with the planning team.

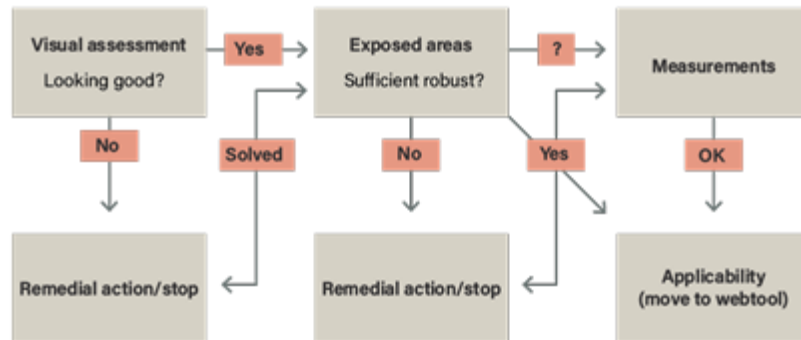
Direct links: [National Building Requirements](#) | [Set your Goal](#)

More information: [www.futurhist.eu](http://www.futurhist.eu) and [www.ribuild.eu](http://www.ribuild.eu)

## INTERNAL INSULATION IN HISTORIC BUILDINGS

## 2 Check what you have

Assess whether the building is a plausible candidate for internal insulation. Start with a visual inspection and look for moisture damage, façade defects, timber decay, spalling, surface mould, algae, defective drainage or other warning signs.



### What to do

- ☐ Identify moisture sources before discussing insulation thickness.
- ☐ Separate defects that can be repaired from risks that require deeper investigation.
- ☐ Document the current condition with photographs, drawings and notes.
- ☐ Use the RiBuild checklists to structure the inspection and documentation.

#### Outcome

By the end of this step, the team should know whether the building can proceed to more detailed assessment or whether remediation is needed first.

Direct links: [Know your building](#) | [Checklists](#)

More information: [www.futurhist.eu](http://www.futurhist.eu) and [www.ribuild.eu](http://www.ribuild.eu)

### 3 Understand risks and constraints

Map the building and its surroundings. Pay attention to driving rain load, moisture-sensitive parts, frost-sensitive materials, rainwater collection and indoor climate, because internal insulation changes the temperature and drying behaviour of the existing wall.

#### Typical damages to check

Use the RIBuild typical-damages pages as a quick visual checklist before moving to insulation-system selection.

| Damage                    | What to look for                                                                | RIBuild link              |
|---------------------------|---------------------------------------------------------------------------------|---------------------------|
| <b>Frost damage</b>       | Scaling of outer masonry surfaces; indicates potential freeze-thaw sensitivity. | <a href="#">Open page</a> |
| <b>Wood rot</b>           | Fungal decay of timber where wood is exposed to high moisture.                  | <a href="#">Open page</a> |
| <b>Mould growth</b>       | Visible or hidden fungal growth on material surfaces in moist conditions.       | <a href="#">Open page</a> |
| <b>Algae growth</b>       | Biofouling films on façades, often linked to wet surfaces.                      | <a href="#">Open page</a> |
| <b>Salt efflorescence</b> | Salt deposits and crystallisation damage on masonry surfaces.                   | <a href="#">Open page</a> |
| <b>Rising damp</b>        | Moisture transported from the ground into porous walls by capillary action.     | <a href="#">Open page</a> |

#### What to do

- ☐ Check exposure and water-shedding details.
- ☐ Locate sensitive embedded elements, such as timber components.
- ☐ Review room use, ventilation and internal moisture loads.

#### Outcome

By the end of this step, the main hygrothermal risks and practical constraints should be clear enough to guide further testing.

Direct links: [Building Information](#)

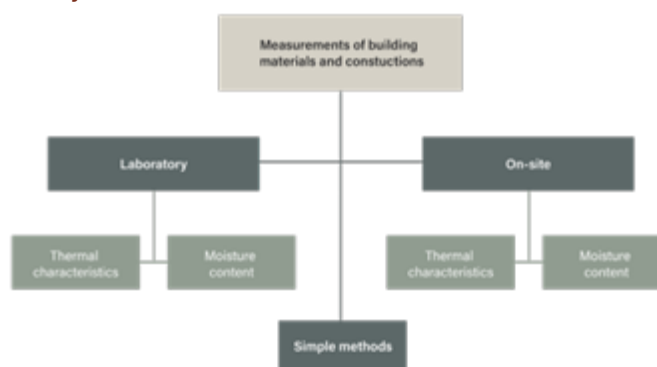
More information: [www.futurhist.eu](http://www.futurhist.eu) and [www.ribuild.eu](http://www.ribuild.eu)

## 4 Collect evidence

Decide whether the available information is sufficient. RIBuild distinguishes between on-site and laboratory measurements. Laboratory measurements can provide higher accuracy, but may require samples such as cores or stone specimens.

|                                                                                                                                                                         |                                                                                                                                                          |                                                                                                                                                                    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>4.1 Building information</b><br>Review the existing building, its construction and surroundings before deciding what to measure.<br><b>Open Building Information</b> | <b>4.2.1 On-site measurements</b><br>Use in-situ methods to document conditions and collect data directly from the building.<br><b>Open Measurements</b> | <b>4.2.2 Laboratory measurements</b><br>Use sample-based tests when more accurate material properties or hygrothermal data are needed.<br><b>Open Measurements</b> |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|

### Measurement hierarchy



### What to do

- ☐ Check building information first: exposure, wall type, moisture-sensitive parts and indoor climate
- ☐ Use on-site measurements for non-destructive or in-situ checks of the existing construction
- ☐ Use laboratory measurements when material properties or more accurate hygrothermal data are required

#### Outcome

By the end of this step, the project team should have a clear evidence base: building information, on-site measurements where useful, and laboratory measurements where necessary.

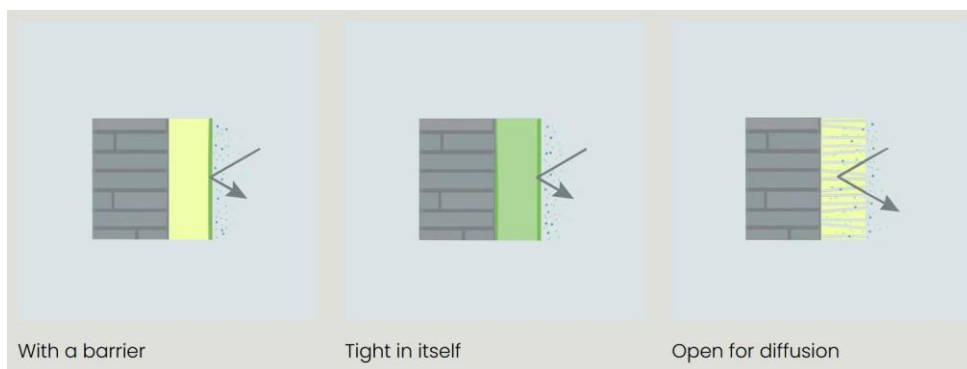
Direct links: [Check your building](#) | [Measurements](#)

More information: [www.futurhist.eu](http://www.futurhist.eu) and [www.ribuild.eu](http://www.ribuild.eu)

## INTERNAL INSULATION IN HISTORIC BUILDINGS

## 5 Identify insulation options

Select a shortlist of possible insulation-system families. RIBuild distinguishes between vapour-tight and vapour-open systems, and between condensate-preventing, condensate-limiting and condensate-tolerating approaches.



### Three types of internal insulation systems

RIBuild distinguishes three internal-insulation system types based on how moisture and vapour transfer are managed.

|                                                                                                                                                                                 |                                                                                                                                                                               |                                                                                                                                                                               |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Condensate-preventing</b><br>Uses a vapour barrier or vapour-tight material to disable vapour transfer from the room side into the construction.<br><b>Open RIBuild type</b> | <b>Condensate-limiting</b><br>Uses a vapour brake/control layer to reduce vapour input while allowing sufficient drying under defined conditions.<br><b>Open RIBuild type</b> | <b>Condensate-tolerating</b><br>Uses capillary-active insulation material and glue mortar; moisture can be absorbed, redistributed and dried out.<br><b>Open RIBuild type</b> |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

### What to do

- ☐ Compare system principles before choosing products.
- ☐ Consider moisture behaviour, installation quality, reversibility and compatibility with existing fabric.
- ☐ Ask for specialist input where moisture-related damage patterns could occur.

#### Outcome

By the end of this step, the team should have a shortlist of technically plausible internal insulation approaches.

Direct links: [Types of Insulations Systems](#)

More information: [www.futurhist.eu](http://www.futurhist.eu) and [www.ribuild.eu](http://www.ribuild.eu)

## INTERNAL INSULATION IN HISTORIC BUILDINGS

## 6 Test performance

Separate two questions that are often mixed together: first, is the insulation option hygrothermally safe for the wall and building context? Second, among the technically acceptable options, what are the energy, environmental and life-cycle cost consequences?



### Two different checks: safety first, then impact and cost

Use hygrothermal safety to decide whether an insulation option is technically acceptable. Use LCA/LCC afterwards to compare the environmental and economic consequences of acceptable options.

#### Hygrothermal safety

Checks moisture and temperature behaviour of the existing wall after insulation. Focus on condensation, drying potential, mould risk, algae risk, frost sensitivity and surface temperature. This is the technical risk gate: unsafe options should be revised or rejected before cost/environmental comparison.

[Open Insulation Calculator Tool](#)

#### LCA/LCC evaluation

Compares the consequences of technically acceptable options. Focus on energy-saving potential, environmental impact and life-cycle cost under defined scenarios. This is the decision optimisation step: it helps choose among options that have already passed the safety check.

[Open LCA/LCC](#)

### What to do

- ☐ **Screen safety:** Check hygrothermal risks using RIBuild system guidance and calculator outputs.
- ☐ **Keep only acceptable options:** Do not compare LCA/LCC for options that remain technically unsafe.
- ☐ **Compare LCA/LCC:** Evaluate energy saving, environmental impact and life-cycle cost for the remaining options.

#### Outcome

By the end of this step, the team should have separated technically acceptable options from rejected/uncertain ones, and should know which remaining options deserve LCA/LCC comparison.

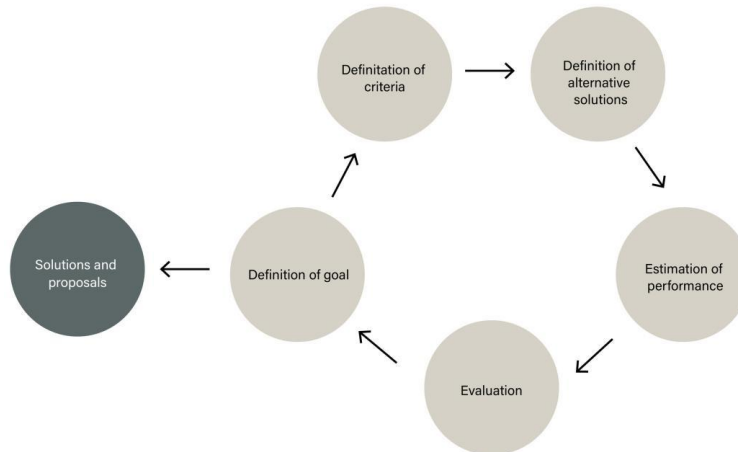
Direct links: [Insulation Systems](#) | [LCA/LCC](#)

More information: [www.futurhist.eu](http://www.futurhist.eu) and [www.ribuild.eu](http://www.ribuild.eu)

## INTERNAL INSULATION IN HISTORIC BUILDINGS

## 7 Evaluate and decide

Compare the remaining options against the initial goals and decision criteria. RIBuild links insulation choices to energy-saving potential, environmental impact and life-cycle cost, so the preferred option should be justified beyond initial thermal performance.



### What to do

- ☐ Compare energy savings with environmental and cost implications.
- ☐ Consider maintenance, replacement and operation over the chosen calculation period.
- ☐ Document why the preferred option is technically and economically justified.

#### Outcome

By the end of this step, the team should be able to decide whether to proceed, revise the proposal, or stop and investigate another retrofit pathway.

Direct links: [Knowledge Base](#)

More information: [www.futurhist.eu](http://www.futurhist.eu) and [www.ribuild.eu](http://www.ribuild.eu)

INTERNAL INSULATION IN HISTORIC BUILDINGS

## Tailored internal insulation strategies for historic buildings

There is no universal internal insulation solution for historic buildings. The most suitable approach depends on project goals, heritage constraints, building condition, moisture exposure, material sensitivity, installation quality and long-term performance.

Use this guide as a quick route through the full RIBuild website. For the complete technical background, calculators and research material, consult the direct links below.

Direct links: [Home](#) | [Set your Goal](#) | [Know your building](#) | [Insulation Systems](#) | [LCA/LCC](#)

## Internal Insulation in Historic Buildings

More information: [www.futurhist.eu](http://www.futurhist.eu) and [www.ribuild.eu](http://www.ribuild.eu)

## 12.2. Component integration guide

Annex 12.2 presents the complete component integration guide. Like Annex 12.1, the final version integrated in the toolkit, the guide will be formatted to follow FuturHist's visual identity, graphic style and layout.

COMPONENT INTEGRATION IN HISTORIC BUILDING RETROFIT

# Integrating Insulation Systems in Historic Building Envelopes

*A Guide for Architects and Consultants*

## **FuturHist decision workflow**

Understand the building -> Identify junctions -> Select compatible details -  
> Verify performance

Based on FuturHist Deliverable D2.8 and complementary retrofit guidance

More information: [www.futurhist.eu](http://www.futurhist.eu) and [Deliverable 2.8](#)

COMPONENT INTEGRATION IN HISTORIC BUILDING RETROFIT

## About this guide

This short guide translates the key messages of FuturHist Deliverable D2.8 into a compact step-by-step workflow. It is designed as a navigation aid for early design discussions rather than as a replacement for the full technical deliverable or project-specific hygrothermal calculations.

Use it to structure conversations between architects, heritage authorities, consultants, contractors and product developers when internal insulation, airtightness and junction detailing must be integrated in historic masonry buildings.

**Direct links:** [FuturHist](#) | [ICOMOS ISCES Knowledge HUB](#)

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Scope: passive envelope retrofit of historic buildings, with emphasis on internal insulation, thermal bridges, airtightness, driving rain protection, rising damp and conservation-compatible component integration.

More information: [www.futurhist.eu](http://www.futurhist.eu) and [Deliverable 2.8](#)

COMPONENT INTEGRATION IN HISTORIC BUILDING RETROFIT

### Welcome!

Energy retrofit in historic buildings is not only a matter of lowering U-values. Junctions, rain exposure, moisture transport, airtightness and heritage constraints can decide whether an insulation strategy performs safely in practice.

FuturHist D2.8 shows that internal insulation can substantially reduce heat losses, but moisture safety and whole-assembly performance depend on climate, wall type, material behaviour, indoor moisture load and junction detailing. The workflow below converts those findings into a practical project route.

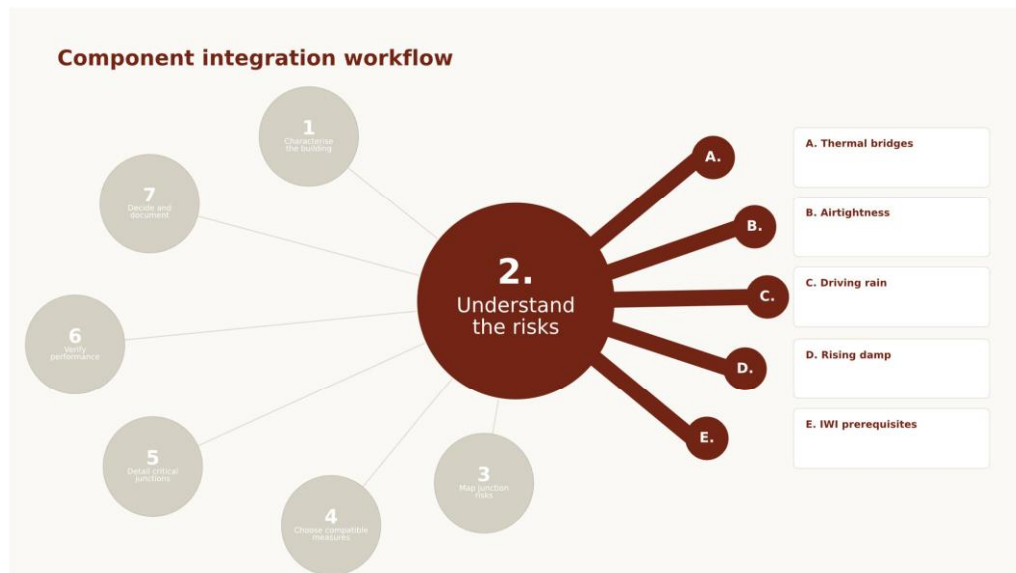
**The process is iterative: if a later step reveals unacceptable moisture risk, thermal bridge risk, conservation conflict or excessive intervention, return to the relevant earlier step and revise the option.**

More information: [www.futurhist.eu](http://www.futurhist.eu) and [Deliverable 2.8](#)

## COMPONENT INTEGRATION IN HISTORIC BUILDING RETROFIT

## Overview: planning component integration

Use this step-by-step guide as a quick route from project framing to integrated retrofit detailing. Each step gives the main task, the practical outcome and links to useful resources.



|                                                                                                                        |                                                                                                                                                                                  |                                                                                                                    |
|------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|
| <b>1 Characterise the building</b><br>Identify typology, wall build-up, exposure, existing damage and sensitive parts. | <b>2 Understand the risks</b><br>Learn ( <a href="#">LINK</a> ) how to screen thermal bridges, airtightness, rain, rising damp and Internal Wall Insulation (IWI) prerequisites. | <b>3 Map junction risks</b><br>Locate thermal bridges, airtightness breaks, rain paths and rising damp risks.      |
| <b>4 Choose compatible measures</b><br>Select measures that fit the typology and conservation constraints.             | <b>5 Detail the critical junctions</b><br>Develop insulation continuity, reveal, plinth, floor, roof and internal wall details.                                                  | <b>6 Verify performance</b><br>Check U-value, $\psi$ -value, fRsi and hygrothermal safety before final comparison. |
| <b>7 Decide and document</b><br>Record accepted options, residual risks, monitoring needs and implementation notes.    | <b>Tip</b><br>Keep the decision record visible: assumptions, limits and accepted risks should travel with the design.                                                            |                                                                                                                    |

Direct links: [FuturHist](#) | [Knowledge HUB](#)

More information: [www.futurhist.eu](http://www.futurhist.eu) and [Deliverable 2.8](#)

## COMPONENT INTEGRATION IN HISTORIC BUILDING RETROFIT

## 1 Characterise the building

A component integration strategy can only be selected after the existing construction is understood. FuturHist typologies cover solid masonry and stone constructions across Spain, Poland, Sweden and Scotland, but each building still needs a project-specific survey.

### Minimum information to collect

| Typology and wall build-up                                                                                                                         | Exposure and water sources                                                                              | Sensitive elements                                                                                                               | Use and indoor climate                                                             |
|----------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| Masonry type, wall thickness, external finish (e.g., plaster), internal finish (e.g., plaster, lath-and-plaster), or previous internal insulation. | Orientation, wind-driven rain, roof overhang, plinth condition, rising damp, drainage and splash zones. | Timber beams, embedded joists, window frames, cornices, skirting boards, decoration and historic surfaces, embedded water pipes. | Occupancy, ventilation, moisture production, heated/unheated attics and basements. |

### What to do

- Document construction layers and thicknesses before calculating retrofit U-values.
- Identify whether external or internal finish, rain protection, drainage, or lath-and-plaster affect the drying behaviour and effectively prevent moisture penetration in the construction.
- Separate repair needs from retrofit measures: defects and water ingress should be solved before insulation is installed.

### Outcome

The team has a typology-based but building-specific understanding of the existing envelope and its moisture vulnerabilities.

More information: [www.futurhist.eu](http://www.futurhist.eu) and [Deliverable 2.8](#)

## 2 Understand the risks

Component integration can be framed around five linked topics: thermal bridges, airtightness, driving rain protection, rising damp and the prerequisites for applying internal insulation. Treat them as a sequence: first understand the existing moisture and exposure conditions, then develop airtight and thermally continuous details, and only then compare insulation options.

### 2.1 Thermal bridges: heat loss and surface temperature risk

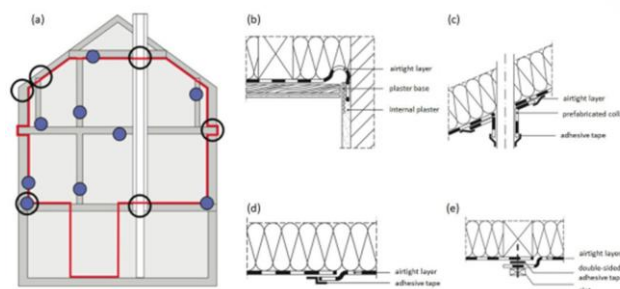
Thermal bridges occur at junctions and penetrations where heat flow is greater than through the adjacent planar element. In internally insulated buildings, their relative importance increases because the temperature difference between wall area and junctions becomes bigger when wall is insulated. Thermal bridge effects in internally insulated constructions can account for up to one-third of total transmission heat loss, so architects should treat junctions as part of the insulation system rather than as secondary details.

|                                 |                                                                                                                                                                                                              |
|---------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Main risks</b>               | Additional heat loss and lower internal surface temperature (local condensation or mould risk).                                                                                                              |
| <b>Key indicator</b>            | Linear thermal transmittance $\psi$ describes additional heat loss at a linear junction.<br>$fR_{si} = (T_{si} - T_e) / (T_i - T_e)$ . Use $fR_{si}$ to screen surface-temperature risk.                     |
| <b>Thresholds</b>               | Define your own threshold depending on your context, for instance for the FuturHist typologies:<br>$fR_{si} \geq 0.70$ for Scotland, Poland and Sweden; $fR_{si} \geq 0.55$ for warm climates such as Spain. |
| <b>Design implication</b>       | Insulation continuity, supplementary insulation, wedges or heat-conducting plates may be needed at floors, reveals and internal walls.                                                                       |
| <b>Architectural constraint</b> | Cornices, skirting boards, window frames and doors can limit supplementary insulation thickness or positioning.                                                                                              |

### 2.2 Airtightness: comfort, heat loss and moisture transport

Air leakage can occur through elements, joints and penetrations. Windows, roof-to-wall connections, chimneys, ventilation pipes and other discontinuities are characterised as typical weak points. Air leakage can reduce comfort through draughts, increase heat loss and transport moisture into vulnerable components. If mechanical ventilation with heat recovery is used, the air must pass through the intended supply and extract routes for the system to operate efficiently.

For design work, draw one continuous airtight layer in red around each section and plan how it crosses every junction. Mark penetrations and element transitions with detail bubbles. This makes the airtightness concept visible early enough to influence insulation layout, service routes and contractor sequencing.



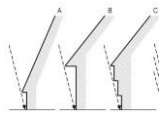
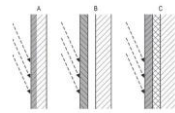
More information: [www.futurhist.eu](http://www.futurhist.eu) and [Deliverable 2.8](#)

## COMPONENT INTEGRATION IN HISTORIC BUILDING RETROFIT

**2.3 Driving rain: exposure, damage and facade protection**

Wind-driven rain depends on wind direction, wind speed, precipitation intensity and airflow at the building envelope. Exposure often peaks at building edges because wind speed and pressure effects are higher there. Rain exposure can cause damage and aesthetic changes such as efflorescence, dirt streaking, erosion and biological growth, and the risk can worsen when drip edges at windowsills, verges and parapets are missing or poorly designed.

Before specifying internal insulation, assess whether the external wall is exposed to wind-driven rain and whether existing render, plaster or masonry can absorb and redistribute water safely. Facade protection is ensured at three levels: design geometry, wall cross-section and surface treatment. For historic facades, conservation compatibility and vapour permeability must be checked before selecting any protective measure.

| Protection route   | Examples                                                            | Architectural/design question                                       | Main caution                                                                       |                                                                                      |
|--------------------|---------------------------------------------------------------------|---------------------------------------------------------------------|------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| Facade geometry    | Roof overhang, recessed facade, water-draining cornice              | Can rain be shed before it reaches vulnerable masonry?              | Often constrained by heritage appearance and limited to already existing features. |   |
| Wall cross-section | Thick/store-capable wall, ventilated outer shell, impermeable layer | Does the wall manage or exclude water as a full assembly?           | Avoid trapping moisture in historic materials.                                     |   |
| Surface protection | Mineral plaster, compatible coating, hydrophobic treatment          | Is capillary uptake reduced while vapour openness remains adequate? | Cracks can concentrate runoff; substrate compatibility is essential.               |  |
| Junction shedding  | Drip edges, runoff profiles, plinth details                         | Are windowsills, parapets and plinths shedding water safely?        | Small details can dominate local wetting.                                          |                                                                                      |

**2.4 Rising damp: diagnose before adding insulation**

Rising damp is capillary water movement from below ground level into porous masonry. Moisture accumulation may be visible as darkening up to a certain height above the ground, and that rising damp threatens both conservation and performance through material degradation, poorer thermal insulation efficiency, unsuitable indoor hygrothermal conditions and reduced mechanical performance.

Do not treat rising damp as a minor side issue. If active rising damp is present, internal wall insulation should not be installed until the moisture source is removed or controlled. Rising damp should be treated as a precondition for proceeding to internal insulation rather than as a detail to solve after the insulation strategy has already been chosen.

More information: [www.futurhist.eu](http://www.futurhist.eu) and [Deliverable 2.8](#)

## COMPONENT INTEGRATION IN HISTORIC BUILDING RETROFIT

| Mitigation principle           | Typical examples to consider                                                                                                        | Architectural/design question                                                            | Main caution                                                                                                  |
|--------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| <b>Reduce ingress</b>          | Sub-soil drainage or other measures that reduce water entry before it reaches the wall. <a href="#">LINK</a>                        | Can soil be drained? Is it possible to excavate around the building?                     | Often constrained in densely built areas. Consider time and budget constraints.                               |
| <b>Reduce wall sorptivity</b>  | Wall cutting, chemical injections or other methods that reduce capillary uptake or wall cross-section. <a href="#">LINK</a>         | Can the solution be correctly implemented? Built-in barriers are preferred over inserts. | A cutting will change the behaviour of the wall accumulating moisture below the barrier.                      |
| <b>Increase evaporation</b>    | Restoration plasters, wall-base ventilation, Knapen tubes, surface heating or other drying-enhancing measures. <a href="#">LINK</a> | Very different design questions depending on the approach chosen.                        | Consider the solution in its context with attention to conflicting conditions and full system specifications. |
| <b>Electrokinetic approach</b> | Active or passive electro-osmosis, with electrodes in the moist wall and ground. <a href="#">LINK</a>                               | No critical questions raised.                                                            | Effectiveness of some of these measures is still under discussion. Consider carefully before committing.      |

**2.5 Recap: Internal insulation prerequisites**

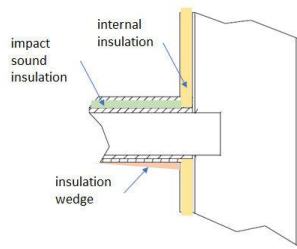
Internal insulation requires careful planning at junctions. IWI can reduce the drying potential of the facade, leaving the external wall cooler and more humid in winter. It can increase moisture-related risks such as freeze-thaw cracking and can exacerbate harmful thermal bridges by reducing internal surface temperatures.

| Precondition before applying IWI              | Design response                                                                                                                                                                                                 |
|-----------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Rising damp</b>                            | Remove or control rising damp before installing internal insulation.                                                                                                                                            |
| <b>Wind-driven rain exposure</b>              | Assess rain exposure and external render absorption; repair cracks before insulating.                                                                                                                           |
| <b>Leaks or wet materials</b>                 | Repair water leaks and allow wet plaster or repair materials to dry before installation.                                                                                                                        |
| <b>Water pipes in the insulated wall</b>      | Shut off and drain embedded heating/hot/cold water pipes; do not apply IWI where active pipes remain.                                                                                                           |
| <b>Surface mould risk</b>                     | Choose material and thickness so fRsi remains above the relevant threshold, including furniture effects.                                                                                                        |
| <b>Window frame connection</b>                | Carry supplementary insulation to the window frame, at least 20 mm where possible, or use an insulation wedge where space is limited.                                                                           |
| <b>Floor-wall and internal-wall junctions</b> | Connect wall insulation to impact sound insulation at floors; consider underside wedges, supplementary insulation along internal walls or heat-conducting plates where protruding solutions are not acceptable. |

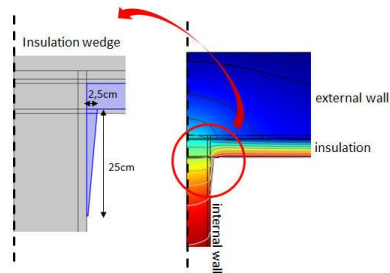
More information: [www.futurhist.eu](http://www.futurhist.eu) and [Deliverable 2.8](#)

COMPONENT INTEGRATION IN HISTORIC BUILDING RETROFIT

floor-external wall connection



Internal wall-external wall connection



**What to do**

- Prepare a one-page risk register for thermal bridges, airtightness, driving rain, rising damp and internal insulation prerequisites.
- For every exposed facade, record rain exposure, surface condition, cracks, render/plaster compatibility and existing water-shedding details.
- For every planned IWI area, verify that rising damp, leaks, wet repair materials and embedded active water pipes have been addressed before design freeze.

**Outcome**

The team has a technically grounded risk screen and a clear set of visual aids and calculations to use before developing junction designs.

More information: [www.futurhist.eu](http://www.futurhist.eu) and [Deliverable 2.8](#)

### 3 Map junction risks

Internal insulation changes heat and moisture paths. Junctions can become colder, local humidity may increase, and discontinuities in airtightness or insulation can significantly increase the moisture risk, even when the insulated wall area performs well.

#### Typical junctions and risks

| Junction                       | Why it matters                                                                              | Typical checks                                                                           |
|--------------------------------|---------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
| Wall-floor / basement / plinth | High heat flow and splash/rising damp exposure; floor type influences losses.               | Insulation continuity, drainage, plinth detailing.                                       |
| Wall-roof / attic              | Wall top can be a strong thermal bridge; heated and unheated attics need different details. | Wall-top insulation, roof insulation continuity, airtight layer continuity.              |
| Wall-ceiling / unheated attic  | Conservation of attic flooring may require insulation below the ceiling.                    | Effect of wall vs ceiling insulation thickness, vapour control, timber safety.           |
| External wall-internal wall    | Internal walls may be loadbearing and connected to external walls, creating cold stripes.   | Need for insulation wedge, impact on historic finishes.                                  |
| Window reveal and frame        | Frame-wall and glass-frame zones can dominate local mould risk.                             | Reveal insulation plaster, frame-wall insulation, airtight sealing, window conservation. |

#### What to do

- Draw a junction risk map before choosing the final insulation build-up.
- Mark every discontinuity of the insulation layer, airtight layer, internal or external finishing impacting on rain shedding or drying potential.
- Use fRsi as a simple surface-temperature risk indicator and  $\psi$ -value to understand junction heat losses.

#### Outcome

The main junctions that could undermine energy savings or create mould/condensation risk are known and prioritised for further analysis.

More information: [www.futurhist.eu](http://www.futurhist.eu) and [Deliverable 2.8](#)

## 4 Choose compatible measures

Component-integration measures can be grouped around four practical questions: reducing thermal bridge losses and mould risk, making airtight layers continuous, protecting facades and junctions from driving rain, and controlling rising damp without unnecessarily invasive interventions.

### Measure families

| Measure family            | Examples                                                                                       | Best use                                                                     | Caution                                                                          |
|---------------------------|------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Thermal bridge mitigation | Insulation wedges, heat-conducting plates                                                      | Use at walls, floors, reveals and internal-wall junctions where fRsi is low. | May conflict with cornices, skirting boards, doors or visible historic finishes. |
| Airtightness strategy     | Internal plaster, airtight membranes, taped/glued panels                                       | Use to avoid convective bypass and moisture transport through cracks/joints. | Needs continuity at junctions and careful detailing around services and windows. |
| Rain protection           | External plaster, hydrophobic treatment, rainscreen, roof overhang, profiles with drip edge    | Use where wind-driven rain and exposed details drive moisture risk.          | Some measures are visually invasive or incompatible with protected facades.      |
| Rising damp response      | Drying-friendly repair, sacrificial plaster, ventilation cavities, injection, moisture barrier | Prefer drying-friendly solutions where conservation constraints are strong.  | Invasive barriers or injections may be irreversible or hard to target correctly. |

### What to do

- Start with the least invasive measure that can satisfy the risk and performance requirements.
- Check whether a measure is not required, already implemented, or not compatible for the typology.
- Give extra scrutiny to rain and rising damp interventions, because these can require changes to facades or load-bearing walls.

### Outcome

The team has a typology-compatible set of measures and knows which options need extra heritage, buildability or moisture review.

More information: [www.futurhist.eu](http://www.futurhist.eu) and [Deliverable 2.8](#)

## 5 Detail the critical junctions

Once measure families are selected, turn them into buildable details. The key principle is continuity: thermal, airtight, rain-shedding and drying functions must connect across junctions without concealing new risks.

### Detailing rules of thumb from the FuturHist examples

| Junction                              | Typology                     | Example                                                                                                                                                               |
|---------------------------------------|------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Wall-basement details                 | Poland – Kamienica           | Increasing the length of plinth insulation reduces $\psi$ , while insufficient insulation thickness can reduce fRsi.                                                  |
| Wall-roof details                     | Poland – Kamienica           | Wall-top insulation is important: a 160 mm wall-top insulation layer can reduce linear thermal transmittance by up to one fourth and increase fRsi by more than 10%.  |
| Unheated attic details                | Poland – Kamienica           | Wall insulation thickness is more relevant than ceiling-insulation thickness for the studied thermal bridge, although increasing both reduces $\psi$ and raises fRsi. |
| Floor slab over the arcaded gallery   | Spain – Casa de pisos        | Wall and floor insulation should form a continuous layer; increasing both wall and floor insulation reduces $\psi$ and increases fRsi.                                |
| External wall-internal wall junctions | Scotland – Georgian tenement | An insulation wedge can be decisive: in the example, only the wedge configuration reaches fRsi > 0.7.                                                                 |
| Window-frame junctions                | Spain – Casa de pisos        | The best case combines insulation plaster on the reveal with insulation at the frame-wall junction, raising fRsi above 0.7 at the frame in the example.               |

### Detail development checklist

- Keep capillary-active materials and drying paths continuous where this is the moisture-safety strategy.
- Avoid convective gaps behind boards or in frame systems; seal perimeters and service penetrations.
- Do not rely on a single detail drawing: check the realised construction sequence and tolerances.
- Document where historic elements prevent ideal continuity and define compensating measures.

#### Outcome

Critical junctions are converted from concepts into coordinated details with explicit assumptions and performance checks.

More information: [www.futurhist.eu](http://www.futurhist.eu) and [Deliverable 2.8](#)

## 6 Verify performance

Verification should separate component-level wall performance from junction-level and moisture-risk checks. A low planar U-value alone is not enough: the same insulation intervention may be acceptable in one climate and risky in another.

### Checks to keep separate

| Check                     | Question                                                                                                         | Typical indicator                                          | Useful resources                                                               |
|---------------------------|------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------|--------------------------------------------------------------------------------|
| Planar wall performance   | How much does the wall heat flow reduce?                                                                         | U-value                                                    | UBAKUS U-value calculator<br>Heat flux tool                                    |
| Interface moisture safety | Could the insulated wall develop mould or condensation risk over time?                                           | MGI, RH, temperature, moisture content                     | Deliverable 2.8, Chapter 2<br>RiBuild calculator<br>Deliverable 2.8, Chapter 4 |
| Thermal bridge losses     | How much heat is lost through junctions?                                                                         | $\psi$ -value                                              | Reuven.tools Thermal Bridge Calculator                                         |
| Surface mould risk        | Are internal surface temperatures sufficiently high?                                                             | fRsi, commonly checked against 0.7 in the studied examples | Reuven.tools Moisture & Mould Risk Calculator                                  |
| Robustness                | Do conclusions change under high indoor moisture load, wind-driven rain, future climate or material uncertainty? | Sensitivity scenarios                                      | Deliverable 2.8, Chapter 2                                                     |

### What to do

- Use conservative boundary conditions for exposed orientations, high indoor moisture load and vulnerable details.
- Treat borderline MGI or fRsi results cautiously and consider additional measurements or design margins.
- Keep technically unsafe options out of later cost or environmental comparison unless they are redesigned.

### Outcome

The team has distinguished acceptable options from uncertain or rejected options and has evidence for the most critical details.

More information: [www.futurhist.eu](http://www.futurhist.eu) and [Deliverable 2.8](#)

## 7 Decide and document

The final decision should explain why the selected strategy is acceptable for the specific building, not only why it performs well in a generic model. Record technical, heritage and implementation assumptions so they remain visible during procurement and construction.

### Decision record

| Record                                    | Why it matters                                                                                                            |
|-------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|
| Selected insulation and junction measures | Prevents later problems with moisture and heritage consequences.                                                          |
| Rejected options and reasons              | Shows whether rejection was due to moisture risk, conservation conflict, cost, buildability or missing data.              |
| Residual uncertainties                    | Identifies where monitoring, inspection or additional calculation is needed.                                              |
| Construction quality points               | Highlights airtightness continuity, full-surface bonding, rain-shedding profiles, membrane overlaps, and site sequencing. |
| Maintenance and monitoring                | Ensures drainage, ventilation, facade condition, indoor RH and sensitive details remain controlled after retrofit.        |

### What to do

- Compare final options against the initial goals and the critical junction checks.
- Include drawings, material assumptions, KPIs and notes on conservation compatibility in the decision package.
- Plan monitoring where risk is sensitive to indoor moisture load, wind-driven rain, workmanship or uncertain material data.

### Outcome

The team can justify whether to proceed, revise, monitor or stop, with a transparent record of technical and conservation reasoning.

More information: [www.futurhist.eu](http://www.futurhist.eu) and [Deliverable 2.8](#)

COMPONENT INTEGRATION IN HISTORIC BUILDING RETROFIT

## Integrated retrofit strategies for historic buildings

There is no universal component-integration solution for historic buildings. The preferred strategy depends on the typology, construction, exposure, indoor moisture load, material sensitivity, heritage constraints and workmanship quality.

Use this guide as a compact route through the technical logic of FuturHist D2.8. For detailed modelling assumptions, material data, typology-specific results and thermal bridge calculations, consult the full deliverable and the additional resources below.

**Direct links:** [FuturHist](#) | [ICOMOS ISCES Knowledge HUB](#)

**Source note:** Prepared from FuturHist D2.8, the RIBuild example guide, and publicly available guidance from ICOMOS ISCES Knowledge HUB. Always verify project-specific decisions with detailed assessment and local regulatory/heritage requirements.

## Internal Insulation in Historic Buildings

More information: [www.futurhist.eu](http://www.futurhist.eu) and [Deliverable 2.8](#)

## 12.3. Input parameters for the energy calculator (PBE)

Annex 12.3 lists the input parameters to perform calculation of the energy need (heating and cooling) using PBE.

Table 16. Building parameters. Name, type and unit, description, default value (if any) and comment/range.

| Input                                 | Type and unit           | Description                                                              | Default | Comment/Range  |
|---------------------------------------|-------------------------|--------------------------------------------------------------------------|---------|----------------|
| <b>BUILDING</b>                       |                         |                                                                          |         |                |
| <b>name</b>                           | str                     | Building name or identifier                                              |         |                |
| <b>azimuth_relative_to_true_north</b> | float (°)               | Orientation of the building relative to north. (0=N, 90=E, 180=S, 270=W) |         |                |
| <b>latitude 1)</b>                    | float                   | Coordinates (used for weather and solar position)                        |         | -90 < x < 90   |
| <b>longitude 1)</b>                   | float                   | Coordinates (used for weather and solar position)                        |         | -180 < x < 180 |
| <b>coldest month</b>                  | float                   | Index of coldest month                                                   |         | 1 ≤ x ≤ 12     |
| <b>exposed_perimeter 2)</b>           | float (m)               | External perimeter                                                       |         | > 0            |
| <b>height</b>                         | float (m)               | Building height (floor to roof)                                          |         | > 0            |
| <b>wall_thickness</b>                 | float (m)               | Average wall layer total thickness                                       |         | > 0            |
| <b>n_floors</b>                       | int                     | Number of floors                                                         |         | Integer > 0    |
| <b>building_type_class</b>            | str                     | Type of building (e.g., <i>Residential_apartment</i> , <i>Office</i> )   |         |                |
| <b>adj_zones_present</b>              | bool                    | Whether unconditioned/adjacent zones exist (YES/NO)                      | NO      |                |
| <b>number_adj_zone</b>                | int                     | Number of adjacent zones                                                 | 0       |                |
| <b>net_floor_area</b>                 | float (m <sup>2</sup> ) | Conditioned floor area                                                   |         | > 0            |
| <b>construction_class</b>             | str                     | Construction quality (e.g., <i>class_i</i> )                             |         | 3)             |

1) In the FuturHist Toolkit it is the ambition to let the users choose 'name of city' from a list, using latitude and longitude as a fallback plan in case a city is not listed.

2) Can be used to do a simple calculation of the thermal bridge coefficient (W/K) in case this is not explicitly given (see Table 23). The fallback if the user does not provide thermal-bridge data: thermal bridge coefficient (W/K) = exposed\_perimeter (m) × 0.05 W/(m·K) — assuming that all thermal bridges run along the external perimeter of the building, with a generic  $\psi$ -value of 0.05. It is not a reliable method for a real project.

3) The construction class determines where the thermal capacity is positioned through the construction: mass concentrated towards the internal side (clai), mass concentrated towards the internal side (e), mass divided between both sides (ie), distributed mass (d), mass concentrated near the middle (m).

Table 17. Opaque building surface parameters. Name, type and unit, description, default value (if any) and comment.

| Input                                                                          | Type and unit              | Description                          | Default                                       | Comment                                                                         |
|--------------------------------------------------------------------------------|----------------------------|--------------------------------------|-----------------------------------------------|---------------------------------------------------------------------------------|
| <b>OPAQUE BUILDING SURFACE (for each element) (assuming no adjacent zones)</b> |                            |                                      |                                               |                                                                                 |
| <b>name</b>                                                                    | str                        | Surface name                         |                                               | 1)                                                                              |
| <b>Type</b>                                                                    |                            | Type of surface                      | opaque                                        |                                                                                 |
| <b>area</b>                                                                    | float (m <sup>2</sup> )    | Surface area                         |                                               | NET area, i.e. excluding area of windows and doors                              |
| <b>sky_view_factor</b>                                                         | float (0-1)                | Fraction of visible sky              | 1.0 (roof),<br>0.5 (vertical),<br>0.0 (floor) | Standard values can be used                                                     |
| <b>u_value</b>                                                                 | float (W/m <sup>2</sup> K) | Thermal transmittance                |                                               | 2)                                                                              |
| <b>solar_absorptance</b>                                                       | float (0-1)                | Fraction of solar radiation absorbed |                                               | Standard values can be used                                                     |
| <b>thermal_capacity</b>                                                        | float (J/Kg K)             | Thermal capacity                     |                                               | Standard values can be used                                                     |
| <b>orientation.azimuth</b>                                                     | float (°)                  | Azimuth                              |                                               | 0 = N, 90 = E, 180 = S, 270 = W                                                 |
| <b>orientation.tilt</b>                                                        |                            | Tilt angle                           | 0 (horizontal),<br>90 (vertical)              | Sloping surfaces (e.g. sloping roofs) not handled in the present version of PBE |

1) Opaque building surfaces can be roofs, vertical surfaces, and slab to ground.

2) U-value for 'slab to ground' shall not include contribution from the ground itself. This is already accounted for in PBE

Table 18. Transparent building surface parameters. Name, type and unit, description, default value (if any) and comment.

| Input                                                                              | Type and unit              | Description                                     | Default          | Comment                                                                                            |
|------------------------------------------------------------------------------------|----------------------------|-------------------------------------------------|------------------|----------------------------------------------------------------------------------------------------|
| <b>TRANSPARENT BUILDING SURFACE (for each element having transparent surfaces)</b> |                            |                                                 |                  |                                                                                                    |
| <b>name</b>                                                                        | str                        | Surface name                                    |                  |                                                                                                    |
| <b>type</b>                                                                        |                            | Type of surface                                 | trans-<br>parent |                                                                                                    |
| <b>area</b>                                                                        | float (m <sup>2</sup> )    | Surface area                                    |                  |                                                                                                    |
| <b>sky view factor</b>                                                             | float (0-1)                | Fraction of visible sky                         |                  | Standard values can be used                                                                        |
| <b>u_value</b>                                                                     | float (W/m <sup>2</sup> K) | Thermal transmittance                           |                  |                                                                                                    |
| <b>solar absorptance</b>                                                           | float (0-1)                | Fraction of solar radiation absorbed            |                  | Standard values can be used                                                                        |
| <b>thermal capacity</b>                                                            | float (J/Kg K)             | Thermal capacity                                | 0                |                                                                                                    |
| <b>orientation.azimuth</b>                                                         | float (°)                  | Window direction                                |                  | 0 = N, 90 = E, 180 = S, 270 = W                                                                    |
| <b>orientation.tilt</b>                                                            | float (°)                  | Window inclination                              | 90               | The shading calculation is presently intended for vertical windows (0 = horizontal, 90 = vertical) |
| <b>height</b>                                                                      | float (m)                  | Height of window                                |                  | Height and width are required to calculate how the sun affects the building                        |
| <b>width</b>                                                                       | float (m)                  | Width of window                                 |                  | Can be handled as the total width of all windows in an opaque surface                              |
| <b>g-value</b>                                                                     | float (0-1)                | Total solar transmittance of the glass          |                  | Fraction of the heat from the sun that enters through a window                                     |
| <b>parapet</b>                                                                     | float (m)                  | Height of parapet below the transparent surface | 1.1              | Value of parapet cannot be larger than height of corresponding opaque building surface             |

Table 19. Transparent building surface parameters referring to shading. Name, type and unit, description, default value (if any) and comment.

| Input                                                                                | Type and unit             | Description                                              | Default             | Comment                                                                    |
|--------------------------------------------------------------------------------------|---------------------------|----------------------------------------------------------|---------------------|----------------------------------------------------------------------------|
| <b>Transparent building surface; additional input in case of any kind of shading</b> |                           |                                                          |                     |                                                                            |
| <b>shading</b>                                                                       | bool                      | Whether shading exists (TRUE) or not (FALSE)             | FALSE               |                                                                            |
| <b>shading type</b>                                                                  |                           | Type of shading                                          | horizontal overhang | Recognized values: "horizontal_overhang", "vertical_overhang", "obstacles" |
| <b>width_or_distance_of_shading_elements</b>                                         | float (m)                 | Distance of overhang above window                        | 0.5                 |                                                                            |
|                                                                                      |                           |                                                          |                     |                                                                            |
| <b>overhang_properties:</b>                                                          |                           | <i>Additional geometric data for shading devices</i>     |                     |                                                                            |
| <b>width_of_horizontal_overhangs</b>                                                 | float (m)                 | Width of horizontal overhangs                            | 1.0                 |                                                                            |
|                                                                                      |                           |                                                          |                     |                                                                            |
| <b>solar_shading_transmittance</b>                                                   | float (0-1)               | Fraction of the sun's energy passing through the shading |                     | 1 means no additional reduction, 0 means complete blocking                 |
| <b>solar_shading_activation_irradiance</b>                                           | float (W/m <sup>2</sup> ) | Irradiance threshold for activating the shading device   |                     | Below the threshold, the solar shading is not activated                    |

The input parameters shown here are based on using horizontal overhangs (permanent overhangs); they might be different using other types of solar shadings.

Table 20. Heating and cooling parameters. Name, type and unit, description, default value (if any) and comment.

| Input                      | Type and unit | Description                 | Default             | Comment                                                                       |
|----------------------------|---------------|-----------------------------|---------------------|-------------------------------------------------------------------------------|
| <b>HEATING AND COOLING</b> |               |                             |                     |                                                                               |
| <i>Heating System</i>      |               |                             |                     |                                                                               |
| <i>Generation system</i>   |               |                             |                     |                                                                               |
| <b>heating_capacity</b>    | float (W)     | Maximum system capacity     | 10 MW               | Use standard values.                                                          |
| <i>Control System</i>      |               |                             |                     |                                                                               |
| <b>heating_setpoint</b>    | float (°C)    | Comfort temperature         | 20                  |                                                                               |
| <b>heating_setback</b>     | float (°C)    | Setback temperature         | 17                  |                                                                               |
|                            |               |                             |                     |                                                                               |
| <b>heating_profile</b>     | float (0-1)   | Heating profile             | 1<br>(all 24 hours) | Select a value for each single hour (24 hours); 0 (no heating, 1 max heating) |
|                            |               |                             |                     | To be filled in for both weekdays and weekend                                 |
| <i>Cooling system</i>      |               |                             |                     |                                                                               |
| <i>Generation System</i>   |               |                             |                     |                                                                               |
| <b>cooling_capacity</b>    | float (W)     | Maximum system capacity     | 12 MW               | Use standard values. Set to 0 if no cooling                                   |
| <i>Control system</i>      |               |                             |                     |                                                                               |
| <b>cooling_setpoint</b>    | float (°C)    | Cooling comfort temperature | 26                  |                                                                               |
| <b>cooling_setback</b>     | float (°C)    | Setback temperature         | 30                  |                                                                               |
|                            |               |                             |                     |                                                                               |
| <b>cooling_profile</b>     | float (0-1)   | Cooling profile             | 0<br>(all 24 hours) | Select a value for each single hour (24 hours); 0 (no cooling, 1 max cooling) |
|                            |               |                             |                     | To be filled in for both weekdays and weekend                                 |

Table 21. Ventilation parameters. Name, type and unit, description, default value (if any) and comment.

| Input                      | Type and unit               | Description         | Default          | Comment                                                                             |
|----------------------------|-----------------------------|---------------------|------------------|-------------------------------------------------------------------------------------|
| <b>VENTILATION</b>         |                             |                     |                  |                                                                                     |
| <b>flow_rate</b>           | float (l/s/m <sup>2</sup> ) | Air change rate     | 0.3              | maximum air change rate                                                             |
| <b>ventilation_profile</b> | float (0-1)                 | Ventilation profile | 1 (all 24 hours) | Select a value for each single hour (24 hours); 0 no ventilation, 1 max ventilation |
|                            |                             |                     |                  | To be filled in for both weekdays and weekend                                       |

Table 22. Internal gains parameters. Name, type and unit, description, default value (if any) and comment.

| Input                                   | Type and unit             | Description                                 | Default          | Comment                                                                                                                                                       |
|-----------------------------------------|---------------------------|---------------------------------------------|------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>INTERNAL GAINS</b>                   |                           |                                             |                  |                                                                                                                                                               |
| <b>Name</b>                             | bool                      | "occupancy",<br>"appliances",<br>"lighting" |                  | Per default all three types of internal gains should be filled in                                                                                             |
| <b>For each type of internal gains:</b> |                           |                                             |                  | If the profile for occupancy, appliances and lighting is the same, only one of them need to be filled in                                                      |
| <b>full_load</b>                        | float (W/m <sup>2</sup> ) | Maximum internal gain                       |                  | Set to 0 for two types of internal gains (e.g. appliances and lighting) if no division is made between internal gains from occupancy, appliances and lighting |
| <b>Internal gains weekdays</b>          |                           |                                             |                  |                                                                                                                                                               |
| <b>weekday</b>                          | float (0-1)               | Internal gains weekday                      | 1 (all 24 hours) | Select a value for each single hour (24 hours); 0 (no internal gain), 1 (max internal gain)                                                                   |
| <b>Internal gains weekend</b>           |                           |                                             |                  |                                                                                                                                                               |
| <b>weekend</b>                          | float (0-1)               | Internal gains weekend                      | 1 (all 24 hours) | Select a value for each single hour (24 hours); 0 (no internal gain), 1 (max internal gain)                                                                   |

Table 23. Thermal bridge parameters. Name, type and unit, description, default value (if any) and comment.

| Input                      | Type and unit | Description          | Default | Comment                                                          |
|----------------------------|---------------|----------------------|---------|------------------------------------------------------------------|
| <b>THERMAL BRIDGES</b>     |               |                      |         |                                                                  |
| <b>thermal_bridge_heat</b> | float (W/K)   | Total thermal bridge |         | Can be based on standard values for linear thermal transmittance |

Using an explicit total value in W/K is the recommended input, including all the different values for linear thermal transmittance, describing the different linear thermal bridges of a specific building and their length. Standard values for linear thermal transmittance can be used, e.g. based on EN ISO 14683:2017 (European Committee for Standardization (CEN), 2017f) or national catalogues for thermal bridges, e.g. the Danish DS 418 (Dansk Standard, 2026). Alternatively, as a simpler approach, the thermal bridge can be described by the total thermal bridge length [m] and a representative value for the linear thermal transmittance [W/(m K)].

## 12.4. Input data for typologies with a demo case (PBE)

For each of the four typologies in FuturHist with a demo case ('typology 1'), annex 12.4 includes values for the input parameters to perform energy calculations using PBE (acc. to the list in Annex 12.3). Typology models refer to the base line scenario, before retrofit. The content represents the typologies as close as possible, esp. based on input from WP5 partners.

Adiabatic surfaces are represented by their area although they were treated differently in the feasibility test, cf. chapter 5.3.2. Scottish typology covers four flats on top of each other, not the whole building in question, to mimic the preconditions set in WP5.

Table 24. Building parameters. Typology 1 (typologies with a demo case).

| Input                              | Typology 1 Spain      | Typology 1 Poland             | Typology 1 Sweden | Typology 1 Scotland   |
|------------------------------------|-----------------------|-------------------------------|-------------------|-----------------------|
| <b>BUILDING</b>                    |                       |                               |                   |                       |
| azimuth_relative_to_true_north [°] | 0                     | 0                             | 0                 | 0                     |
| latitude, longitude [°]            | 37.85, -4.85          | 50.04, 19.56                  | 58.42, 15.58      | 55.94, -3.20          |
| coldest month                      | 1                     | 1                             | 1                 | 1                     |
| exposed_perimeter [m]              | 36.68                 | 76.37                         | 130               | 45.4                  |
| height [m]                         | 10                    | 13.2 (15.9 from cellar floor) | 10.7              | 12.4                  |
| wall_thickness [m]                 | 0.44                  | 0.55                          | 0.6               | 0.7                   |
| n_floors                           | 3                     | 4 (only 2 heated)             | 3                 | 4                     |
| building_type_class                | Residential apartment | Residential apartment         | Office            | Residential apartment |
| adj_zones_present                  | FALSE                 | FALSE                         | FALSE             | FALSE                 |
| number_adj_zone                    | 0                     | 0                             | 0                 | 0                     |
| net_floor_area [m <sup>2</sup> ]   | 157.56                | 486.74                        | 2007              | 496.8                 |
| construction_class                 | Class d               | Class d                       | Class d           | Class d               |

Table 25. Heating and cooling parameters. Typology 1 (typologies with a demo case).

| Input                      | Typology 1 Spain              | Typology 1 Poland | Typology 1 Sweden | Typology 1 Scotland                     |
|----------------------------|-------------------------------|-------------------|-------------------|-----------------------------------------|
| <b>HEATING AND COOLING</b> |                               |                   |                   |                                         |
| <i>Heating System</i>      |                               |                   |                   |                                         |
| <i>Generation system</i>   |                               |                   |                   |                                         |
| heating_capacity [W]       | 23600                         | 41000             | unlimited         | 7000 <sup>1)</sup>                      |
| <i>Control System</i>      |                               |                   |                   |                                         |
| heating_setpoint [°C]      | 20                            | 20                | 21                | 21                                      |
| heating_setback [°C]       | 17                            | 18                | 21                | 18                                      |
| heating_profile_weekdays   | 23-7; 0<br>7-23; 1            | 1 (all 24 hours)  | 1 (all 24 hours)  | 0-7; 0<br>7-9; 1<br>9-16; 0<br>16-24; 1 |
| heating_profile_weekend    | As weekdays                   | 1 (all 24 hours)  | 1 (all 24 hours)  | As weekdays                             |
| <i>Cooling system</i>      |                               |                   |                   |                                         |
| <i>Generation System</i>   |                               |                   |                   |                                         |
| cooling_capacity [W]       | 15800                         | No                | No                | N/A                                     |
| <i>Control system</i>      |                               |                   |                   |                                         |
| cooling_setpoint [°C]      | 25-27                         | No                | No                | 25                                      |
| cooling_setback [°C]       | NA                            | No                | No                | 30                                      |
| cooling_profile_weekdays   | 0-7; 1<br>7-15; 0<br>15-24; 1 | 0 (all 24 hours)  | 0 (all 24 hours)  | 0 (all 24 hours)                        |
| cooling_profile_weekend    | As weekdays                   | 0 (all 24 hours)  | 0 (all 24 hours)  | 0 (all 24 hours)                        |

1) Boiler capacity per flat; typology covers four flats

Table 26. Ventilation parameters. Typology 1 (typologies with a demo case).

| Input                                     | Typology 1 Spain                  | Typology 1 Poland | Typology 1 Sweden             | Typology 1 Scotland |
|-------------------------------------------|-----------------------------------|-------------------|-------------------------------|---------------------|
| <b>VENTILATION</b>                        |                                   |                   |                               |                     |
| flow_rate [l/s/m <sup>2</sup> ] (maximum) | 0.48                              | 0.3               | 0.833                         | 0.37                |
| ventilation_profile_weekdays              | 0-8; 1<br>8-17; 0.347<br>17-24; 1 | 1 (all 24 hours)  | 0-7; 0<br>7-18; 1<br>18-24; 0 | 1 (all 24 hours)    |
| ventilation_profile_weekend               | 1 (all 24 hours)                  | 1 (all 24 hours)  | 0 (all 24 hours)              | 1 (all 24 hours)    |

Table 27. Internal gains parameters. Typology 1 (typologies with a demo case).

| Input                            | Typology 1 Spain                                                                               | Typology 1 Poland | Typology 1 Sweden             | Typology 1 Scotland                                                     |
|----------------------------------|------------------------------------------------------------------------------------------------|-------------------|-------------------------------|-------------------------------------------------------------------------|
| INTERNAL GAINS                   |                                                                                                |                   |                               |                                                                         |
| name                             | For all four typologies, there are no separate profiles for occupancy, appliances and lighting |                   |                               |                                                                         |
| For each type of internal gains: |                                                                                                |                   |                               |                                                                         |
| full_load [W/m²]                 | 4.6                                                                                            | 13                | 27.5 <sup>1)</sup>            | 4.2                                                                     |
| Internal gains weekdays          |                                                                                                |                   |                               |                                                                         |
| weekday                          | 0-7; 0.29<br>7-15; 0.31<br>15-18; 0.35<br>18-19; 0.5<br>19-23; 0.88<br>23-24; 0.62             | 1 (all 24 hours)  | 0-8; 0<br>8-17; 1<br>17-24; 0 | 0-5; 1<br>5-8; 0.47<br>8-20; 0<br>20-22; 0.47<br>22-24; 1 <sup>2)</sup> |
| Internal gains weekend           |                                                                                                |                   |                               |                                                                         |
| weekend                          | 0-7; 0.31<br>7-18; 0.48<br>18-19; 0.62<br>19-23; 0.1<br>23-24; 0.62                            | 1 (all 24 hours)  | 0 (all 24 hours)              | as for workdays                                                         |

1) divided into 10 W/m<sup>2</sup> (occupancy), 7.5 W/m<sup>2</sup> (appliances), 10 W/m<sup>2</sup> (lighting), all with the same profile

2) profile for master bedroom, as given by Scottish partner, which might not be representative for a residential building, esp. not in weekends

Table 28. Thermal bridge parameters. Typology 1 (typologies with a demo case).

| Input                         | Typology 1<br>Spain | Typology 1<br>Poland | Typology 1<br>Sweden | Typology 1<br>Scotland |
|-------------------------------|---------------------|----------------------|----------------------|------------------------|
| thermal_bridges_heat<br>[W/K] | 14.03               | 3.8 <sup>1)</sup>    | 570 <sup>2)</sup>    | 13.35                  |

1) As no data was available, default values based on external perimeter [m] and a generic thermal bridge coefficient (0,05 W/(m K) was used, only covering thermal bridges at the ground (fallback option included in PBE).

2) Data from Swedish partner based on the assumption that 30 % of the heat loss comes from thermal bridges. It was acknowledged that is probably too high for a building of the period covered by this typology (1850-1920).

## Data for opaque and transparent surfaces, Spain

Opaque building surface areas are given as net area, i.e. without windows, cf. Table 17.

Table 29. Opaque building surfaces. Typology 1, Spain. Vertical surfaces.

| Input                          | North                  |                        | South                |
|--------------------------------|------------------------|------------------------|----------------------|
| Name                           | Opaque north surface 1 | Opaque north surface 2 | Opaque south surface |
| area [m <sup>2</sup> ]         | 33.0                   | 23.4                   | 50.52                |
| sky_view_factor                | 0.6                    | 0.6                    | 0.6                  |
| u_value [W/(m <sup>2</sup> K)] | 0.59                   | 1.08                   | 1.08                 |
| solar_absorptance              | 0.6                    | 0.6                    | 0.6                  |
| thermal_capacity [J/(kg K)]    | 364728                 | 1292000                | 1221360              |
| orientation.azimuth [°]        | 0                      | 0                      | 180                  |
| orientation.tilt [°]           | 90                     | 90                     | 90                   |

Table 30. Opaque building surfaces. Typology 1, Spain. Vertical surfaces (ctd.).

| Input                          | East                |                                 | West                            |
|--------------------------------|---------------------|---------------------------------|---------------------------------|
| Name                           | Opaque east surface | Opaque east surface (adiabatic) | Opaque west surface (adiabatic) |
| area [m <sup>2</sup> ]         | 48.0                | 40.92                           | 97.17                           |
| sky_view_factor                | 0.6                 | 0.6                             | 0.6                             |
| u_value [W/(m <sup>2</sup> K)] | 0.59                | 0 <sup>1)</sup>                 | 0 <sup>1)</sup>                 |
| solar_absorptance              | 0.6                 | 0.6                             | 0.6                             |
| thermal_capacity [J/(kg K)]    | 364728              | 1221360                         | 217571                          |
| orientation.azimuth [°]        | 90                  | 180                             | 270                             |
| orientation.tilt [°]           | 90                  | 90                              | 90                              |

1) u-value set to 0, cf. adiabatic surfaces.

Table 31. Opaque building surfaces. Typology 1, Spain. Horizontal surfaces.

| Input                          | Roof              |                      | Slab to ground          |                       |
|--------------------------------|-------------------|----------------------|-------------------------|-----------------------|
|                                | Roof surface_flat | Roof surface_pitched | Slab to ground entrance | Slab to ground arcade |
| Name                           |                   |                      |                         |                       |
| area [m <sup>2</sup> ]         | 29.45             | 38.58                | 22.58                   | 31.8                  |
| sky_view_factor                | 1.0               | 1.0                  | 0.6 <sup>2)</sup>       | 0.6 <sup>2)</sup>     |
| u_value [W/(m <sup>2</sup> K)] | 0.79              | 0.93                 | 2.1                     | 2.19                  |
| solar_absorptance              | 0.6               | 0.6                  | 0.6 <sup>2)</sup>       | 0.6 <sup>2)</sup>     |
| thermal_capacity [J/(kg K)]    | 653082            | 91000                | 555119                  | 432667                |
| orientation.azimuth [°]        | 0                 | 0                    | 0                       | 0                     |
| orientation.tilt [°]           | 0                 | 30 <sup>*)</sup>     | 0                       | 0                     |

1) PBE can only handle vertical or horizontal surfaces. In the feasibility test tilt was set to 0 degrees (horizontal)

2) Slab to ground is represented by the floor above the entrance and an arcade respectively, as the ground floor is not heated. In case of a slab to ground located at the earth below the building (which would be the normal situation), the value if these parameters would be 0.0. In a specific building with an arcade the value of 0.6 for these parameters should be considered carefully.

Table 32. Transparent building surfaces. Typology 1, Spain.

| Input                          | North                     | East                     | South                     | West                     |
|--------------------------------|---------------------------|--------------------------|---------------------------|--------------------------|
| name                           | Transparent north surface | Transparent east surface | Transparent south surface | Transparent west surface |
| type                           | Transparent               | Transparent              | Transparent               | Transparent              |
| area [m <sup>2</sup> ]         | 5.88                      | 0.01 <sup>1)</sup>       | 25.35                     | 0.01 <sup>1)</sup>       |
| sky view factor                | 0.6                       | 0.6                      | 0.6                       | 0.6                      |
| u_value [W/(m <sup>2</sup> K)] | 3.86                      | 3.86                     | 3.92                      | 3.86                     |
| solar absorptance              | 0.1                       | 0.1                      | 0.1                       | 0.1                      |
| thermal capacity [W]           | 0.0                       | 0.0                      | 0.0                       | 0.0                      |
| orientation .azimuth [°]       | 0                         | 90                       | 180                       | 270                      |
| orientation.tilt [°]           | 90                        | 90                       | 90                        | 90                       |
| height [m]                     | 1.18                      | 0.1                      | 2.11                      | 0.1                      |
| length (width) [m]             | 5.0                       | 0.1                      | 12                        | 5.0                      |
| g-value                        | 0.8                       | 0.75                     | 0.8                       | 0.75                     |
| parapet [m]                    | 0.8                       | 0.1                      | 0.0                       | 0.1                      |

1) There are no windows towards east and west in the demo case that represents the typology. Therefore, area is set to 0.01 m<sup>2</sup> (0 does not work in Python). In other buildings this might not be the case, for which these surfaces are kept in the model.

Table 33. Transparent building surfaces (ctd.). Typology 1, Spain.

| Input                                                                                | North               | East                | South               | West                |
|--------------------------------------------------------------------------------------|---------------------|---------------------|---------------------|---------------------|
| <b>Transparent building surface; additional input in case of any kind of shading</b> |                     |                     |                     |                     |
| shading                                                                              | TRUE                | FALSE               | TRUE                | FALSE               |
| shading type                                                                         | horizontal overhang | horizontal overhang | horizontal overhang | horizontal overhang |
| width_or_distance_of_shading_elements                                                | 1.0                 | 0.0 <sup>1)</sup>   | 1.09                | 0.0 <sup>1)</sup>   |
|                                                                                      |                     |                     |                     |                     |
| <i>overhang_properties:</i>                                                          |                     |                     |                     |                     |
| width_of_horisontal_overhangs                                                        | 0.7                 | 0.0 <sup>1)</sup>   | 0.7                 | 0.0 <sup>1)</sup>   |
|                                                                                      |                     |                     |                     |                     |
| solar_shading_transmittance                                                          | 0.20                | - <sup>2)</sup>     | 0.20                | - <sup>2)</sup>     |
| solar_shading_activation_irradiance                                                  | 200.0               | - <sup>2)</sup>     | 200.0               | - <sup>2)</sup>     |

1) Not important which values to use as 'shading' is set to FALSE = shading not activated in the calculations

2) Not activated, cf. FALSE

## Data for opaque and transparent surfaces, Poland

Opaque building surface areas are given as net area, i.e. without windows, cf. Table 17.

Table 34. Opaque building surfaces. Typology 1, Poland. Vertical surfaces.

| Input                         | North                | East                |                                 | South                |
|-------------------------------|----------------------|---------------------|---------------------------------|----------------------|
| Name and type                 | Opaque north surface | Opaque east surface | Opaque east surface (adiabatic) | Opaque south surface |
| area [m <sup>2</sup> ]        | 151.28               | 122.84              | 72.03                           | 104.31               |
| sky_view_factor               | 0.5                  | 0.5                 | 0.0                             | 0.5                  |
| u_value [W(m <sup>2</sup> K)] | 1.14                 | 1.14                | 0 <sup>1)</sup>                 | 1.14                 |
| solar_absorptance             | 0.6                  | 0.6                 | 0.0                             | 0.6                  |
| thermal_capacity [J/(kg K)]   | 158248               | 158248              | 158248                          | 158248               |
| orientation.azimuth [°]       | 0                    | 90                  | 90                              | 180                  |
| orientation.tilt [°]          | 90                   | 90                  | 90                              | 90                   |

1) U-value set to 0, cf. adiabatic surface.

Table 35. Opaque building surfaces. Typology 1, Poland. Vertical surfaces. (ctd.)

| Input                         | West                |                                 | Southwest                |
|-------------------------------|---------------------|---------------------------------|--------------------------|
| Name and type                 | Opaque west surface | Opaque west surface (adiabatic) | Opaque southwest surface |
| area [m <sup>2</sup> ]        | 25.95               | 154.72                          | 17.41                    |
| sky_view_factor               | 0.5                 | 0.0                             | 0.5                      |
| u_value [W(m <sup>2</sup> K)] | 1.14                | 0 <sup>1)</sup>                 | 1.14                     |
| solar_absorptance             | 0.6                 | 0.0                             | 0.6                      |
| thermal_capacity [J/(kg K)]   | 158248              | 158248                          | 158248                   |
| orientation.azimuth [°]       | 270                 | 270                             | 225 <sup>2)</sup>        |
| orientation.tilt [°]          | 90                  | 90                              | 90                       |

1) U-value set to 0, cf. adiabatic surface.

2) PBE can only handle vertical surfaces towards N, E, S, or W. In the feasibility test orientation was set to 180 degrees (South).

Table 36. Opaque building surfaces. Typology 1, Poland. Horizontal surfaces.

| Input                          | Roof                  | Slab to ground          |
|--------------------------------|-----------------------|-------------------------|
| Name and type                  | Roof surface (opaque) | Slab to ground (opaque) |
| area [m <sup>2</sup> ]         | 242.91                | 243.37                  |
| sky_view_factor                | 1.0                   | 0.0                     |
| u_value [W/(m <sup>2</sup> K)] | 1.82                  | 1.4                     |
| solar_absorptance              | 0.6                   | 0.0                     |
| thermal_capacity [J/(kg K)]    | 49265                 | 153680                  |
| orientation.azimuth [°]        | 0                     | 0                       |
| orientation.tilt [°]           | 0                     | 0                       |

Table 37. Transparent building surfaces. Typology 1, Poland.

| Input                          | North                     | East                     | South                     | West                     | Southwest                     |
|--------------------------------|---------------------------|--------------------------|---------------------------|--------------------------|-------------------------------|
| name                           | Transparent north surface | Transparent east surface | Transparent south surface | Transparent west surface | Transparent southwest surface |
| type                           | Transparent               | Transparent              | Transparent               | Transparent              | Transparent                   |
| area [m <sup>2</sup> ]         | 18.0                      | 0.1 <sup>1)</sup>        | 15.0                      | 1.6                      | 6.4                           |
| sky view factor                | 0.5                       | 0.5                      | 0.5                       | 0.5                      | 0.5                           |
| u_value [W/(m <sup>2</sup> K)] | 2.5                       | 2.5                      | 2.5                       | 2.5                      | 2.5                           |
| solar absorptance              | 0.6                       | 0.65                     | 0.6                       | 0.6                      | 0.6                           |
| thermal capacity [W]           | 0.0                       | 0.0                      | 0.0                       | 0.0                      | 0.0                           |
| orientation.alpha azimuth [°]  | 0                         | 90                       | 180                       | 270                      | 225 <sup>2)</sup>             |
| orientation.tilt [°]           | 90                        | 90                       | 90                        | 90                       | 90                            |
| Height [m]                     | 2.13                      | 2.13                     | 2.15                      | 2.2                      | 2.12                          |
| Length (width) [m]             | 8.57                      | 0.05                     | 7.07                      | 0.74                     | 3.0                           |
| g-value                        | 0.65                      | 0.65                     | 0.65                      | 0.65                     | 0.65                          |
| parapet [m]                    | 1.1                       | 1.1                      | 1.1                       | 1.1                      | 1.1                           |

1) No windows towards east in the demo case that represents the typology. Therefore, area is set to 0.1 m<sup>2</sup> (0 does not work in Python). In other buildings this might not be the case, for which this surface is kept in the model.

2) PBE can only handle vertical surfaces oriented towards N, E, S or W. In the feasibility test orientation was set to 180 degrees (South)

Table 38. Transparent building surfaces (ctd.). Typology 1, Poland.

| Input                                                                                | North               | East                | South               | West                | Southwest           |
|--------------------------------------------------------------------------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| <b>Transparent building surface; additional input in case of any kind of shading</b> |                     |                     |                     |                     |                     |
| Shading                                                                              | FALSE               | FALSE               | FALSE               | FALSE               | FALSE               |
| shading type                                                                         | horizontal overhang | horizontal overhang | horizontal overhang | horizontal overhang | horizontal overhang |
| width_or_distance_of_shading_elements <sup>1)</sup>                                  | 0.5                 | 0.5                 | 0.5                 | 0.5                 | 0.5                 |
|                                                                                      |                     |                     |                     |                     |                     |
| <i>overhang_properties:</i>                                                          |                     |                     |                     |                     |                     |
| width_of_horizontal_overhangs <sup>1)</sup>                                          | 1.0                 | 1.0                 | 1.0                 | 1.0                 | 1.0                 |
|                                                                                      |                     |                     |                     |                     |                     |
| solar_shading_transmittance                                                          | _ 2)                | _ 2)                | _ 2)                | _ 2)                | _ 2)                |
| solar_shading_activation_irradiance                                                  | _ 2)                | _ 2)                | _ 2)                | _ 2)                | _ 2)                |

1) Default values; as 'shading' is set to FALSE = shading not activated in the calculations, these values are of no importance

2) Not activated

## Data for opaque and transparent surfaces, Sweden

Opaque building surface areas are given as net area, i.e. without windows, cf. Table 17.

Table 39. Opaque building surfaces. Typology 1, Sweden. Vertical surfaces.

| Input                          | North                | East                | South                | West                |
|--------------------------------|----------------------|---------------------|----------------------|---------------------|
| Name and type                  | Opaque north surface | Opaque east surface | Opaque south surface | Opaque west surface |
| area [m <sup>2</sup> ]         | 271                  | 227                 | 331                  | 227                 |
| sky_view_factor                | 0.6                  | 0.6                 | 0.6                  | 0.6                 |
| u_value [W/(m <sup>2</sup> K)] | 0.78                 | 0.78                | 0.78                 | 0.78                |
| solar_absorptance              | 0.5                  | 0.5                 | 0.5                  | 0.5                 |
| thermal_capacity [J/(kg K)]    | 718200               | 718200              | 718200               | 718200              |
| orientation.azimuth [°]        | 0                    | 90                  | 180                  | 270                 |
| orientation.tilt [°]           | 90                   | 90                  | 90                   | 90                  |

Table 40. Opaque building surfaces. Typology 1, Sweden. Horizontal surfaces.

| Input                          | Roof                  | Slab to ground          |
|--------------------------------|-----------------------|-------------------------|
| Name and type                  | Roof surface (opaque) | Slab to ground (opaque) |
| area [m <sup>2</sup> ]         | 740                   | 625                     |
| sky_view_factor                | 1.0                   | 0.0                     |
| u_value [W/(m <sup>2</sup> K)] | 0.58                  | 3.48                    |
| solar_absorptance              | 0.5                   | 0.0                     |
| thermal_capacity [J/(kg K)]    | 280700                | 625000                  |
| orientation.azimuth [°]        | 0                     | 0                       |
| orientation.tilt [°]           | 0                     | 0                       |

Table 41. Transparent building surfaces. Typology 1, Sweden.

| Input                          | North                     | East                     | South                     | West                     |
|--------------------------------|---------------------------|--------------------------|---------------------------|--------------------------|
| name                           | Transparent north surface | Transparent east surface | Transparent south surface | Transparent west surface |
| type                           | Transparent               | Transparent              | Transparent               | Transparent              |
| area [m <sup>2</sup> ]         | 62.0                      | 22.0                     | 64.0                      | 15.0                     |
| sky view factor                | 0.7                       | 0.7                      | 0.7                       | 0.7                      |
| u_value [W/(m <sup>2</sup> K)] | 2.2                       | 2.2                      | 2.2                       | 2.2                      |
| solar absorptance              | 0.5                       | 0.5                      | 0.5                       | 0.5                      |
| thermal capacity [W]           | 0.0                       | 0.0                      | 0.0                       | 0.0                      |
| orientation .azimuth [°]       | 0                         | 90                       | 180                       | 270                      |
| orientation.tilt [°]           | 90                        | 90                       | 90                        | 90                       |
| height [m]                     | 1.92                      | 1.92                     | 1.92                      | 1.92                     |
| length (width) [m]             | 32.3                      | 11.5                     | 33.3                      | 7.8                      |
| g-value                        | 0.76                      | 0.76                     | 0.54 <sup>1)</sup>        | 0.76                     |
| parapet [m]                    | 1.1                       | 1.1                      | 1.1                       | 1.1                      |

1) See note 1) below Table 42.

Table 42. Transparent building surfaces (ctd.). Typology 1, Sweden.

| Input                                                                                | North               | East                | South <sup>1)</sup> | West                |
|--------------------------------------------------------------------------------------|---------------------|---------------------|---------------------|---------------------|
| <b>Transparent building surface; additional input in case of any kind of shading</b> |                     |                     |                     |                     |
| Shading                                                                              | FALSE               | FALSE               | FALSE               | FALSE               |
| shading type                                                                         | horizontal overhang | horizontal overhang | horizontal overhang | horizontal overhang |
| width_or_distance_of_shading_elements <sup>2)</sup>                                  | 0.5                 | 0.5                 | 0.5                 | 0.5                 |
|                                                                                      |                     |                     |                     |                     |
| <i>overhang_properties:</i>                                                          |                     |                     |                     |                     |
| width_of_horizontal_overhangs <sup>2)</sup>                                          | 1.0                 | 1.0                 | 1.0                 | 1.0                 |
|                                                                                      |                     |                     |                     |                     |
| solar_shading_transmittance                                                          | _ 3)                | _ 3)                | _ 3)                | _ 3)                |
| solar_shading_activation_irradiance                                                  | _ 3)                | _ 3)                | _ 3)                | _ 3)                |

1) The Swedish typology includes solar shading towards south. The solar shading is activated by sunlight. For simplicity this is handled by setting the g-value for the windows to 0.54 (windows without shading: 0.76), using a Swedish standard factor (0.71) used to account for behaviour-controlled solar shading by adjusting the window g-value.

Alternatively shading should be set to TRUE and values for the four parameters included should be chosen to represent the sun shading.

2) Not important which values to use as 'shading' is set to FALSE = shading not activated in the calculations

3) Not activated

## Data for opaque and transparent surfaces, Scotland

Opaque building surface areas are given as net area, i.e. without windows, cf. Table 17.

Table 43. Opaque building surfaces. Typology 1, Scotland. Vertical surfaces.

| Input                          | North                | East                   | South                | West                   |
|--------------------------------|----------------------|------------------------|----------------------|------------------------|
| Name and type                  | Opaque north surface | Opaque east surface *) | Opaque south surface | Opaque west surface *) |
| area [m <sup>2</sup> ]         | 87.66                | 167.4                  | 87.66                | 167.4                  |
| sky_view_factor                | 0.6                  | 0.6                    | 0.6                  | 0.6                    |
| u_value [W/(m <sup>2</sup> K)] | 1.35                 | 0                      | 1.35                 | 0                      |
| solar_absorptance              | 0.6                  | 0.6                    | 0.6                  | 0.6                    |
| thermal_capacity [J/(kg K)]    | 757120               | 757120                 | 757120               | 757120                 |
| orientation.azimuth [°]        | 0                    | 90                     | 180                  | 270                    |
| orientation.tilt [°]           | 90                   | 90                     | 90                   | 90                     |

\*) : Adiabatic surfaces, i.e. u-value set to 0.

Table 44. Opaque building surfaces. Typology 1, Scotland. Horizontal surfaces.

| Input                          | Roof                       | Slab to ground          |
|--------------------------------|----------------------------|-------------------------|
| Name and type                  | Roof surface_flat (opaque) | Slab to ground (opaque) |
| area [m <sup>2</sup> ]         | 124.2                      | 22.58                   |
| sky_view_factor                | 0.5                        | 0.0                     |
| u_value [W/(m <sup>2</sup> K)] | 0.6                        | 2.1                     |
| solar_absorptance              | 0.6                        | 0.0                     |
| thermal_capacity [J/(kg K)]    | 757120                     | 280000                  |
| orientation.azimuth [°]        | 0                          | 0                       |
| orientation.tilt [°]           | 0                          | 0                       |

Table 45. Transparent building surfaces. Typology 1, Scotland.

| Input                          | North                     | East                     | South                     | West                     |
|--------------------------------|---------------------------|--------------------------|---------------------------|--------------------------|
| name                           | Transparent north surface | Transparent east surface | Transparent south surface | Transparent west surface |
| type                           | Transparent               | Transparent              | Transparent               | Transparent              |
| area [m <sup>2</sup> ]         | 26.42                     | 0.01 *)                  | 26.42                     | 0.01 *)                  |
| sky view factor                | 0.6                       | 0.5                      | 0.6                       | 0.5                      |
| u_value [W/(m <sup>2</sup> K)] | 5.6                       | 5.6                      | 5.6                       | 5.6                      |
| solar absorptance              | 0.6                       | 0.6                      | 0.6                       | 0.6                      |
| thermal capacity [W]           | 0.0                       | 0.0                      | 0.0                       | 0.0                      |
| orientation .azimuth [°]       | 0                         | 90                       | 0                         | 90                       |
| orientation.tilt [°]           | 90                        | 90                       | 90                        | 90                       |
| height [m]                     | 2.1                       | 0.1                      | 2.1                       | 0.1                      |
| length (width) [m]             | 12.58                     | 0.1                      | 12.58                     | 0.1                      |
| g-value                        | 0.88                      | 0.88                     | 0.88                      | 0.88                     |
| parapet [m]                    | 1.1                       | 1.1                      | 1.1                       | 1.1                      |

\*) : There are no windows towards east and west in the demo case that represents the typology. Therefore, area is set to 0.01 m<sup>2</sup> (0 does not work in Python). In other buildings this might not be the case, for which these surfaces are kept in the model.

Table 46. Transparent building surfaces (ctd.). Typology 1, Scotland.

| Input                                                                                | North               | East                | South               | West                |
|--------------------------------------------------------------------------------------|---------------------|---------------------|---------------------|---------------------|
| <b>Transparent building surface; additional input in case of any kind of shading</b> |                     |                     |                     |                     |
| Shading                                                                              | FALSE               | FALSE               | FALSE               | FALSE               |
| shading type                                                                         | horizontal overhang | horizontal overhang | horizontal overhang | horizontal overhang |
| width_or_distance_of_shading_elements <sup>1)</sup>                                  | 0.5                 | 0.5                 | 0.5                 | 0.5                 |
|                                                                                      |                     |                     |                     |                     |
| <i>overhang_properties:</i>                                                          |                     |                     |                     |                     |
| width_of_horizontal_overhangs <sup>1)</sup>                                          | 1.0                 | 1.0                 | 1.0                 | 1.0                 |
|                                                                                      |                     |                     |                     |                     |
| solar_shading_transmittance                                                          | _ 2)                | _ 2)                | _ 2)                | _ 2)                |
| solar_shading_activation_irradiance                                                  | _ 2)                | _ 2)                | _ 2)                | _ 2)                |

1) Not important which values to use as 'shading' is set to FALSE = shading not activated in the calculations

2) Not activated

## 12.5. IEQ guide

This annex presents the content of the FuturHist guide for indoor environment quality (IAQ) and the references used in chapter 6.

### Assessing existing Building Performance

#### Understanding the Building

Historic buildings were constructed using techniques and materials that often differ significantly from those used today. Their performance depends not only on their original design but also on years of repairs, alterations and changing patterns of use. Before considering any retrofit intervention, it is important to understand how the building functions, including the relationship between its structure, building fabric, services and occupants.

Gathering information through drawings, historical records, maintenance documentation and site inspections provides a valuable starting point. This understanding helps identify the building's strengths, recognise existing problems and avoid retrofit solutions that may unintentionally damage the building or reduce indoor environmental quality.

#### Good practice

- Review historical drawings and available documentation.
- Record previous alterations and repairs.
- Consider the building as an integrated system rather than a collection of individual elements.
- Engage specialists where heritage significance requires expert advice.

**Key message:** A thorough understanding of the building is the foundation of every successful retrofit.

**More information:** <https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/>  
<https://www.historicenvironment.scot/publications/all/publication/?publicationId=47c9f2eb-1ade-4a76-a775-add0008972f3>  
<https://historicengland.org.uk/images-books/publications/planning-responsible-retrofit-of-traditional-buildings>

#### Construction Types

Historic buildings across Europe encompass a wide variety of construction methods, including solid masonry, timber frame, stone, brick, earth construction and mixed structural systems. Each

responds differently to heat, moisture and air movement, influencing both indoor environmental quality and retrofit options.

Understanding how walls, roofs, floors and windows were originally designed to perform helps determine appropriate improvement measures. Retrofit solutions should always be compatible with the construction type to avoid unintended consequences such as trapped moisture, thermal bridging or structural deterioration.

### Good practice

- Identify the construction system before specifying retrofit measures.
- Recognise that different building elements may have been added during different periods.
- Consider how traditional construction manages moisture and ventilation.
- Avoid applying identical solutions to every historic building.

**Key message:** Different construction types require different retrofit strategies.

**More information:** <https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/>  
<https://www.historicenvironment.scot/publications/all/publication/?publicationId=47c9f2eb-1ade-4a76-a775-add0008972f3>

### Traditional Materials

Many historic buildings rely on natural materials such as stone, brick, timber, lime mortar, clay and slate. These materials often regulate moisture by absorbing and releasing water vapour, contributing to the building's long-term durability and indoor comfort.

Introducing incompatible modern materials may alter this balance, leading to moisture accumulation, material deterioration or reduced indoor environmental quality. Whenever possible, retrofit interventions should maintain the original behaviour of traditional materials while improving thermal and environmental performance.

### Good practice

- Identify original materials before intervention.
- Select compatible repair and insulation materials.
- Preserve breathable construction wherever appropriate.
- Replace historic materials only when repair is no longer feasible.

**Key message:** Compatible materials help protect both the building and its indoor environment.

**More information:** <https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/traditional-buildings-and-energy-efficiency/properties-of-traditional-building-construction/>  
[https://www.historicenvironment.scot/publications/all/publication/?publicationId=47c9f2eb-1ade-4a76-a775-add0008972f3https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814\\_SRG+ed2\\_Digital+V2\\_compressed.pdf](https://www.historicenvironment.scot/publications/all/publication/?publicationId=47c9f2eb-1ade-4a76-a775-add0008972f3https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814_SRG+ed2_Digital+V2_compressed.pdf)

## Building Pathology

Building pathology is the study of defects and their underlying causes. Common issues in historic buildings include dampness, timber decay, cracking, salt contamination, biological growth and weathering. These defects are often symptoms of wider problems rather than isolated failures.

Understanding why deterioration has occurred is essential before undertaking retrofit work. Addressing the root cause, rather than simply treating visible damage, reduces the likelihood of recurring problems and supports the long-term performance of both the building and its occupants.

### Good practice

- Investigate the cause of defects before repairs.
- Distinguish between cosmetic damage and structural concerns.
- Document existing defects before retrofit begins.
- Seek specialist advice for significant structural or heritage issues.

**Key message:** Successful retrofit addresses the causes of defects, not just their symptoms.

**More information:** <https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/improving-energy-efficiency-through-mitigation>  
[https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814\\_SRG+ed2\\_Digital+V2\\_compressed.pdf](https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814_SRG+ed2_Digital+V2_compressed.pdf)

## Occupancy and Building Use

The way a building is used significantly influences indoor environmental quality. Occupancy patterns, heating schedules, ventilation habits, and indoor activities all affect temperature, humidity, air quality, and energy consumption. Buildings designed for one purpose may perform differently when their use changes.

Understanding how occupants interact with the building helps identify opportunities to improve comfort and building performance. Retrofit measures should support everyday use while recognising that user behaviour remains an important part of achieving good indoor environmental conditions.

### Good practice

- Identify how different spaces are used.
- Consider occupancy schedules and seasonal variations.
- Discuss comfort concerns with building users where possible.
- Design retrofit measures that are simple to operate.

**Key message:** Building performance depends on both the building itself and the people who use it.

## Indoor Environmental Assessment

Assessing the indoor environment provides valuable information about the conditions occupants experience before a retrofit begins. Key aspects include thermal comfort, indoor air quality, lighting, acoustics and moisture conditions, all of which contribute to health, wellbeing and productivity.

A combination of visual inspections, occupant feedback and indoor environmental monitoring provides the most complete picture of building performance. This baseline assessment helps identify existing problems and enables evaluation of improvements once retrofit measures have been completed.

### Good practice

- Assess all aspects of indoor environmental quality.
- Combine measurements with occupant feedback.
- Identify seasonal variations where possible.
- Record baseline conditions before intervention.

**Key message:** Understanding existing indoor conditions is essential for measuring retrofit success.

**More information:** <https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/improving-energy-efficiency-through-mitigation>

## Building Surveys and Diagnostics

Building surveys provide detailed information about the condition and performance of the building fabric and services. Surveys may include visual inspections, moisture investigations, thermography, airtightness testing and assessments of heating and ventilation systems.

Selecting appropriate diagnostic methods helps identify hidden defects that may not be visible during routine inspections. Survey results should inform retrofit decisions, ensuring that interventions respond to actual building conditions rather than assumptions.

### Good practice

- Carry out surveys before finalising retrofit designs.
- Use non-destructive techniques whenever possible.
- Combine different diagnostic methods to improve understanding.
- Record findings systematically for future reference.

**Key message:** Good decisions depend on reliable information about the building's current condition.

More information: <https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/whole-building-approach-for-historic-buildings/stage-1-gather-data-and-surveys/>  
<https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/whole-building-approach-for-historic-buildings/stage-2-assess-and-plan/>

## Monitoring Indoor Environmental Conditions

Monitoring provides objective evidence of how a building performs under real operating conditions. Parameters such as temperature, relative humidity, carbon dioxide concentration and, where appropriate, particulate matter can reveal patterns that are not apparent during short site visits.

Monitoring before and after retrofit helps evaluate whether interventions have improved comfort, indoor air quality and energy performance. Continuous monitoring also supports ongoing building management and helps identify emerging problems before they become significant.

### Good practice

- Monitor conditions over representative periods.
- Place sensors in occupied spaces away from direct heat sources or sunlight.

- Interpret monitoring results alongside occupancy patterns.
- Compare conditions before and after retrofit where possible.

**Key message:** Monitoring provides evidence that supports better retrofit decisions and building management.

**More information:** <https://historicengland.org.uk/images-books/publications/planning-responsible-retrofit-of-traditional-buildings>

## Identifying Risks and Priorities

Not every issue can be addressed at the same time, making it important to identify priorities before developing a retrofit strategy. Risks may include poor indoor air quality, overheating, dampness, structural deterioration, excessive energy use or risks to heritage significance.

Priorities should balance occupant health and comfort, building conservation, technical feasibility, cost and long-term performance. A phased approach may allow improvements to be delivered progressively, reducing disruption and making the best use of available resources.

### Good practice

- Prioritise issues affecting health and safety.
- Consider both short-term improvements and long-term resilience.
- Balance energy performance with heritage conservation.
- Develop a phased retrofit plan where appropriate.

**Key message:** Prioritising the right interventions helps achieve effective, balanced and sustainable retrofit outcomes.

**More information:** <https://historicengland.org.uk/images-books/publications/planning-responsible-retrofit-of-traditional-buildings>  
[https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814\\_SRG+ed2\\_Digital+V2\\_compressed.pdf](https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814_SRG+ed2_Digital+V2_compressed.pdf)

# Thermal Comfort

## Thermal Comfort in Historic Buildings

Thermal comfort describes how satisfied people feel with the indoor thermal environment. It is influenced by air temperature, radiant temperature, humidity, air movement, clothing and activity levels. Historic buildings often experience greater temperature variation than modern buildings due to their construction, original heating systems and natural ventilation. Occupants

may therefore adapt their behaviour by changing clothing, opening windows or adjusting heating to remain comfortable.

Improving thermal comfort should focus on providing stable and appropriate indoor conditions rather than achieving a fixed temperature throughout the building. Retrofit measures should consider both winter and summer performance, recognising that interventions affecting one season may influence comfort in another. Solutions should also respect the building's original construction and avoid compromising its long-term performance.

### Good practice

- Consider thermal comfort throughout the year.
- Assess both winter and summer conditions before retrofit.
- Recognise that occupants may have different comfort preferences.
- Balance comfort improvements with heritage conservation objectives.

**Key message:** Improving thermal comfort means creating healthier, more stable indoor conditions while respecting the way historic buildings perform.

### More information:

[https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814\\_SRG+ed2\\_Digital+V2\\_compressed.pdf](https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814_SRG+ed2_Digital+V2_compressed.pdf)

<https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/traditional-buildings-and-energy-efficiency/occupants-wellbeing/>

## Heating & Cooling Strategies

Heating and cooling systems should work with the building rather than against it. Many historic buildings were designed to operate without modern mechanical cooling and relied on passive measures such as thermal mass, natural ventilation and solar shading. Retrofit provides an opportunity to improve thermal comfort by combining these traditional features with efficient modern technologies where appropriate.

Heating systems should provide consistent and controllable temperatures while avoiding rapid fluctuations that may affect occupants or historic materials. Where cooling is required, passive approaches should always be considered first, with mechanical systems introduced only where necessary and designed to minimise visual impact, energy consumption and disturbance to the historic fabric.

### Good practice

- Prioritise passive heating and cooling measures where feasible.

- Improve heating controls to match occupancy patterns.
- Avoid excessive indoor temperatures during winter.
- Select systems that can be installed with minimal impact on historic features.

**Key message:** Well-designed heating and cooling strategies combine traditional building performance with efficient modern technologies.

**More information:**

[https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814\\_SRG+ed2\\_Digital+V2\\_compressed.pdf](https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814_SRG+ed2_Digital+V2_compressed.pdf)

## Cooling and Overheating

Although historic buildings are often associated with cold conditions, overheating is becoming an increasing concern across Europe as temperatures rise and heatwaves become more frequent. Buildings that have undergone energy efficiency improvements may also retain more heat if ventilation and solar gains are not carefully managed.

Reducing overheating should begin with passive measures such as external shading, appropriate window operation, night-time ventilation and the effective use of thermal mass. Mechanical cooling should only be considered when passive strategies cannot maintain acceptable indoor conditions or where building use requires tighter environmental control.

**Good practice**

- Assess overheating risk before selecting retrofit measures.
- Reduce unwanted solar gains through shading where appropriate.
- Encourage night-time ventilation during warm periods where safe and practical.
- Consider future climate conditions as well as current weather.

**Key message:** Managing overheating is becoming an essential part of climate-resilient retrofit.

**More information:**

[https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814\\_SRG+ed2\\_Digital+V2\\_compressed.pdf](https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814_SRG+ed2_Digital+V2_compressed.pdf)

## Moisture, Condensation and Mould

Moisture is one of the most common causes of deterioration in historic buildings and can significantly affect indoor environmental quality. Excess moisture may result from rain penetration, rising damp, plumbing leaks, condensation or everyday occupant activities such as

cooking, bathing and drying clothes. Persistent damp conditions increase the risk of mould growth, material decay and poor indoor air quality.

Condensation occurs when warm, moisture-loaded air comes into contact with colder surfaces. Retrofit measures that increase airtightness or alter the building fabric should always consider how moisture will be managed. Improving insulation, reducing thermal bridges and maintaining adequate ventilation can help minimise condensation while protecting both occupants and historic materials.

### Good practice

- Investigate the source of moisture before carrying out repairs.
- Maintain adequate ventilation in moisture-producing spaces.
- Reduce thermal bridges where possible.
- Monitor areas with a history of dampness or mould.

**Key message:** Effective moisture management protects both building fabric and occupant health.

### More information:

[https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814\\_SRG+ed2\\_Digital+V2\\_compressed.pdf](https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814_SRG+ed2_Digital+V2_compressed.pdf)

## Building Fabric Improvements

Improving the thermal performance of the building fabric can reduce heat loss, enhance comfort and lower energy demand. Measures may include upgrading roofs, walls, floors, windows and doors, while carefully considering the original construction and moisture behaviour of the building.

Not every building requires the same level of intervention. In some cases, targeted improvements combined with better heating controls and ventilation may deliver significant benefits while reducing the need for extensive alterations. Retrofit measures should always be compatible with existing materials and avoid creating new moisture or durability problems.

### Good practice

- Improve the thermal performance of the building envelope where appropriate.
- Retain and repair existing elements whenever feasible.
- Select insulation systems compatible with traditional construction.
- Consider the interaction between insulation, ventilation and moisture movement.

**Key message:** Building fabric improvements should enhance thermal performance without compromising the building's long-term durability.

**More information:**

[https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814\\_SRG+ed2\\_Digital+V2\\_compressed.pdf](https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814_SRG+ed2_Digital+V2_compressed.pdf)  
<https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/upgrading-thermal-elements-installing-insulation>  
<https://www.historicenvironment.scot/publications/all/publication/?publicationId=47c9f2eb-1ade-4a76-a775-add0008972f3>

## Managing Thermal Performance while Preserving Heritage Value

Historic buildings have cultural, architectural and social significance that should be respected throughout the retrofit process. Improving thermal performance does not necessarily require extensive alteration or the replacement of historic features. In many cases, sensitive and well-planned interventions can achieve meaningful improvements while preserving the building's character.

Retrofit decisions should consider the significance of individual building elements, the reversibility of interventions and the long-term performance of the building. Collaboration between building owners, designers, engineers and conservation professionals can help identify solutions that balance comfort, energy efficiency and heritage conservation.

**Good practice**

- Understand the heritage significance of the building before intervention.
- Prioritise repair and maintenance before replacement.
- Use reversible solutions where practical.
- Balance energy performance with conservation objectives throughout the design process.

**Key message:** Successful retrofit improves thermal performance while safeguarding the historic character and significance of the building.

**More information:**

[https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814\\_SRG+ed2\\_Digital+V2\\_compressed.pdf](https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814_SRG+ed2_Digital+V2_compressed.pdf)  
<https://historicengland.org.uk/images-books/publications/planning-responsible-retrofit-of-traditional-buildings>  
<https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/improving-energy-efficiency-through-mitigation#BPE>

## Indoor Air Quality

### Key Indoor Pollutants and Sources

Indoor air quality (IAQ) plays an important role in the health, comfort and wellbeing of building occupants. Pollutants found indoors originate from a range of sources, including outdoor air, occupant activities, building materials, furnishings and heating or cooking appliances. Common indoor pollutants include carbon dioxide (CO<sub>2</sub>), particulate matter (PM), volatile organic compounds (VOCs), nitrogen dioxide (NO<sub>2</sub>), carbon monoxide (CO) and biological contaminants such as mould spores.

Historic buildings may face particular IAQ challenges due to ageing building services, moisture problems or changes introduced during previous refurbishments. Understanding the likely sources of pollution is the first step in selecting appropriate ventilation, maintenance and retrofit strategies that improve indoor air quality while respecting the building's heritage value.

### Good practice

- Identify both indoor and outdoor pollution sources.
- Consider occupant activities that affect air quality.
- Assess heating, cooking and combustion appliances where present.
- Address pollution sources before relying solely on ventilation.

**Key message:** Improving indoor air quality begins with understanding where pollutants originate.

**More information:** <https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/traditional-buildings-and-energy-efficiency/occupants-wellbeing/>  
[https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6159a391b40bec28e045f6cc/1741372215960/HEMAC Home User Guide ON SCREEN.pdf](https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6159a391b40bec28e045f6cc/1741372215960/HEMAC+Home+User+Guide+ON+SCREEN.pdf)

### Ventilation Principles

Ventilation supplies fresh outdoor air while removing excess heat, moisture and indoor pollutants. Effective ventilation helps maintain healthy indoor conditions, reduces the risk of condensation and supports occupant comfort. In historic buildings, ventilation often occurs naturally through windows, chimneys, vents and small air leakage paths within the building fabric.

Retrofit measures that improve airtightness can reduce uncontrolled heat loss, but they may also reduce natural air exchange if ventilation is not considered. Achieving the right balance between

energy efficiency and adequate ventilation is essential to maintaining healthy indoor environments and protecting the building fabric.

### Good practice

- Consider ventilation as part of the overall retrofit strategy.
- Ensure adequate fresh air is provided after improving airtightness.
- Maintain existing ventilation paths where they contribute to building performance.
- Design ventilation systems that are simple for occupants to understand and operate.

**Key message:** Good ventilation is essential for both healthy occupants and healthy buildings.

**More information:** <https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/traditional-buildings-and-energy-efficiency/properties-of-traditional-building-construction/>

## Natural Ventilation in Historic Buildings

Many historic buildings were designed to rely on natural ventilation rather than mechanical systems. Windows, chimneys, roof spaces and other architectural features often work together to provide air movement, helping remove moisture and maintain acceptable indoor conditions throughout the year.

Where natural ventilation performs effectively, it should be retained and enhanced wherever possible. However, changes in building use, increased occupancy or improved airtightness may reduce its effectiveness. Evaluating how air currently moves through the building helps determine whether natural ventilation alone remains sufficient or whether additional measures are needed.

### Good practice

- Understand existing airflow patterns before making alterations.
- Retain traditional ventilation features where practical.
- Avoid blocking vents or chimneys without assessing their role.
- Encourage occupants to use windows appropriately where safe and practical.

**Key message:** Natural ventilation remains an important asset in many historic buildings and should be considered before introducing mechanical solutions.

### More information:

<https://www.historicenvironment.scot/publications/all/publication/?publicationId=ff550899->

[9512-4eba-a823-a59800a7b97d](https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6159a391b40bec28e045f6cc/1741372215960/HEMAC_Home_User_Guide_ON_SCREEN.pdf)

[https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6159a391b40bec28e045f6cc/1741372215960/HEMAC\\_Home\\_User\\_Guide\\_ON\\_SCREEN.pdf](https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6159a391b40bec28e045f6cc/1741372215960/HEMAC_Home_User_Guide_ON_SCREEN.pdf)

## Mechanical Ventilation Solutions

Where natural ventilation cannot provide sufficient fresh air, mechanical ventilation may be an appropriate solution. Modern systems can improve indoor air quality by supplying controlled amounts of outdoor air while extracting stale air, reducing pollutant concentrations and managing indoor humidity. Heat recovery systems may also improve energy efficiency by recovering heat from outgoing air.

Mechanical ventilation should be carefully designed to minimise impacts on the historic fabric and character of the building. Installation routes, equipment location and maintenance requirements should all be considered during the design process. Systems should also be easy to operate and maintained regularly to ensure long-term performance.

### Good practice

- Consider mechanical ventilation only after assessing passive options.
- Select systems that minimise intervention to historic fabric.
- Ensure ventilation systems are properly commissioned and maintained.
- Provide occupants with clear guidance on system operation.

**Key message:** Mechanical ventilation can improve indoor air quality when carefully integrated into historic buildings.

**More information:** <https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/improving-energy-efficiency-through-mitigation/risks-of-energy-efficiency-interventions/>

[https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6159a391b40bec28e045f6cc/1741372215960/HEMAC\\_Home\\_User\\_Guide\\_ON\\_SCREEN.pdf](https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6159a391b40bec28e045f6cc/1741372215960/HEMAC_Home_User_Guide_ON_SCREEN.pdf)

## Moisture and Indoor Air Quality

Indoor moisture has a direct influence on air quality and occupant health. Excess humidity can encourage mould growth, increase dust mite populations and damage building materials, while very dry conditions may affect comfort and respiratory health. Everyday activities such as cooking, showering, cleaning and drying clothes contribute significant amounts of indoor moisture.

Managing moisture requires a balanced approach that combines adequate ventilation, appropriate heating and careful management of the building fabric. Retrofit measures should

reduce the likelihood of condensation while preserving the ability of traditional materials to regulate moisture naturally.

### Good practice

- Control indoor moisture at its source where possible.
- Ventilate kitchens, bathrooms and other moisture-producing areas.
- Maintain consistent indoor temperatures during colder months.
- Inspect regularly for signs of dampness or mould growth.

**Key message:** Controlling indoor moisture is essential for maintaining good air quality and protecting historic buildings.

**More information:** <https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/traditional-buildings-and-energy-efficiency/occupants-wellbeing/>  
[https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814\\_SRG+ed2\\_Digital+V2\\_compressed.pdf](https://static1.squarespace.com/static/5978a800bf629a80c569eef0/t/6522c0c2b3c33a33cd6709dc/1741372215960/230814_SRG+ed2_Digital+V2_compressed.pdf)

## Monitoring Indoor Air Quality

Monitoring indoor air quality provides objective information about the conditions experienced by occupants and helps identify issues that may not be immediately visible. Measurements may include carbon dioxide, temperature, relative humidity, particulate matter and, where appropriate, volatile organic compounds or other pollutants depending on the building and its use.

Monitoring before and after retrofit allows building owners and practitioners to evaluate the effectiveness of interventions and identify areas requiring further improvement. Long-term monitoring can also support building management by detecting changes in performance and informing maintenance decisions.

### Good practice

- Measure key indoor environmental parameters over representative periods.
- Position sensors in occupied areas away from direct heat sources or windows.
- Interpret monitoring data alongside occupancy and building operation.
- Repeat measurements after retrofit to evaluate performance.

**Key message:** Monitoring transforms indoor air quality from assumptions into measurable evidence.

## Healthy Indoor Air During and After Retrofit

Retrofit activities can temporarily affect indoor air quality through dust generation, emissions from construction products and reduced ventilation during building works. Careful planning can minimise disruption and protect both occupants and construction workers throughout the project.

After retrofit, good indoor air quality depends on appropriate ventilation, suitable material selection, effective moisture management and regular maintenance of building systems. Low-emission products, adequate ventilation during commissioning and clear guidance for occupants can all contribute to healthier indoor environments and help ensure that retrofit delivers long-term benefits.

### Good practice

- Protect occupied spaces from dust during construction.
- Select low-emission materials and finishes where possible.
- Ventilate the building thoroughly before reoccupation.
- Provide occupants with guidance on operating heating and ventilation systems after retrofit.

**Key message:** Achieving healthy indoor air is an ongoing process that begins during retrofit and continues throughout the building's operation.

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## 12.6. LCA calculator – insulation database

The following is the database used for LCA calculator for insulation solutions, in its current completeness.

| Solution ID                        | Solution Name                                                                                      | Build-up Description                                                                       | Substructure Factor | Substructure is Variable?           | Substructure Lifespan [Years] | Substructure Embodied GHG (A1-A3) | Substructure End-of-Life GHG (C3-C4) | Substructure Data Source | Insulation Factor | Insulation is Variable?             | Insulation Minimum Thickness [mm] | Insulation Maximum Thickness [mm] | Insulation Lifespan [Years] | Insulation Embodied GHG (A1-A3) | Insulation End-of-Life GHG (C3-C4) | Insulation Data Source | Finish Factor          | Finish Lifespan [Years] | Finish Embodied GHG (A1-A3) | Finish End-of-Life GHG (C3-C4) | Finish Data Source     |                        |
|------------------------------------|----------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|---------------------|-------------------------------------|-------------------------------|-----------------------------------|--------------------------------------|--------------------------|-------------------|-------------------------------------|-----------------------------------|-----------------------------------|-----------------------------|---------------------------------|------------------------------------|------------------------|------------------------|-------------------------|-----------------------------|--------------------------------|------------------------|------------------------|
| Internal Wall Insulation solutions |                                                                                                    |                                                                                            |                     |                                     |                               |                                   |                                      |                          |                   |                                     |                                   |                                   |                             |                                 |                                    |                        |                        |                         |                             |                                |                        |                        |
| IWI1                               | Aerogel blanket/matt                                                                               | Steel screws<br>10 mm aerogel blanket/matt<br>10 mm interior plaster                       | 0.051282051         | <input type="checkbox"/>            | 50                            | 4183                              | 0.0007481                            | <a href="#">Source</a>   | 1                 | <input type="checkbox"/>            |                                   |                                   |                             | 50                              | 12.8                               | 0                      | <a href="#">Source</a> | 0.01                    | 50                          | 203.2                          | 14.95                  | <a href="#">Source</a> |
| IWI3                               | Aerogel insulating plaster                                                                         | 35 mm insulating plaster                                                                   |                     | <input type="checkbox"/>            |                               |                                   |                                      |                          | 7.0875            | <input type="checkbox"/>            |                                   |                                   |                             | 50                              | 4.39                               | 0.00467                | <a href="#">Source</a> |                         |                             |                                |                        |                        |
| IWI4                               | Autoclaved cellular concrete (AAC)                                                                 | 10 mm light mineral mortar<br>20-300 mineral insulation boards<br>10 mm interior plaster   | 10                  | <input type="checkbox"/>            | 50                            | 0.564                             | 0.0169                               | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 20                                | 300                               | 50                          | 123                             | 2.296                              | <a href="#">Source</a> | 0.01                   | 50                      | 203.2                       | 14.95                          | <a href="#">Source</a> |                        |
| IWI5                               | Calcium silicate boards                                                                            | 10 mm light mineral mortar<br>50-100 calcium silicate board<br>10 mm lime plaster          | 10                  | <input type="checkbox"/>            | 50                            | 0.564                             | 0.0169                               | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 50                                | 100                               | 50                          | 556.5                           | 5.983                              | <a href="#">Source</a> | 0.01                   | 50                      | 193.9                       | 14.95                          | <a href="#">Source</a> |                        |
| IWI6                               | Calciumsilicate board with core made of high-performance insulation material (PU, foam glass, VIP) | 10 mm light mineral mortar<br>15-150 calcium silicate thermal composite board              | 10                  | <input type="checkbox"/>            | 50                            | 0.564                             | 0.0169                               | <a href="#">Source</a>   | 0.000259          | <input checked="" type="checkbox"/> | 15                                | 150                               | 80                          | 1400                            | 56.6                               | <a href="#">Source</a> | 0.01                   | 50                      | 193.9                       | 14.95                          | <a href="#">Source</a> |                        |
| IWI7                               | Cellulose (loose/blown-in/dry application)                                                         | 40-220 mm timber construction<br>40-220 mm blown in cellulose<br>12.5 mm plasterboard      | 0.0001              | <input checked="" type="checkbox"/> | 50                            | -629.4                            | 863                                  | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 40                                | 220                               | 50                          | -72.72                          | 84.14                              | <a href="#">Source</a> | 1                      | 50                      | 1.708                       | 0.7705                         | <a href="#">Source</a> |                        |
| IWI8                               | Cellulose (wet application)                                                                        | 50-100 mm timber construction<br>50-100 mm sprayed cellulose<br>12.5 mm plasterboard       | 0.0001              | <input checked="" type="checkbox"/> | 50                            | -629.4                            | 863                                  | <a href="#">Source</a>   | 0.057             | <input checked="" type="checkbox"/> | 50                                | 100                               | 50                          | -1.23                           | 1.35                               | <a href="#">Source</a> | 1                      | 50                      | 1.708                       | 0.7705                         | <a href="#">Source</a> |                        |
| IWI11                              | Cork insulation                                                                                    | Steel screws<br>50-300 mm cork board<br>12.5 mm plasterboard                               | 0.006153846         | <input checked="" type="checkbox"/> | 50                            | 4183                              | 0.0007481                            | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 50                                | 300                               | 50                          | -85.08                          | 128.3                              | <a href="#">Source</a> | 1                      | 50                      | 1.708                       | 0.7705                         | <a href="#">Source</a> |                        |
| IWI12                              | Flax insulation                                                                                    | 50-150 mm timber construction<br>50-150 flax thermal board<br>12.5 mm plasterboard         | 0.0001              | <input checked="" type="checkbox"/> | 50                            | -629.4                            | 863                                  | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 50                                | 150                               | 50                          | 64.07                           | 76.07                              | <a href="#">Source</a> | 1                      | 50                      | 1.708                       | 0.7705                         | <a href="#">Source</a> |                        |
| IWI13                              | Foam glass                                                                                         | 10 mm glue mortar<br>40-200 mm foam glass board<br>10 mm interior plaster                  | 150                 | <input type="checkbox"/>            | 50                            | 8.045                             | 2.21                                 | <a href="#">Source</a>   | 0.165             | <input checked="" type="checkbox"/> | 40                                | 200                               | 50                          | 2.391                           | 0.01963                            | <a href="#">Source</a> | 0.01                   | 50                      | 203.2                       | 14.95                          | <a href="#">Source</a> |                        |
| IWI14                              | Hemp fibre                                                                                         | 100-200 mm timber construction<br>100-200 mm hemp fibre board<br>12.5 mm plasterboard      | 0.0001              | <input checked="" type="checkbox"/> | 50                            | -629.4                            | 863                                  | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 100                               | 200                               | 50                          | -20.3                           | 55.8                               | <a href="#">Source</a> | 1                      | 50                      | 1.708                       | 0.7705                         | <a href="#">Source</a> |                        |
| IWI15                              | Hemp+lime insulation                                                                               | 60-200 mm timber construction<br>60-200 mm hempcrete insulation<br>10 mm interior plaster  | 0.0001              | <input checked="" type="checkbox"/> | 50                            | -629.4                            | 863                                  | <a href="#">Source</a>   | 0.00333           | <input checked="" type="checkbox"/> | 60                                | 200                               | 100                         | -26.77                          | -3.83                              | <a href="#">Source</a> | 0.01                   | 50                      | 203.2                       | 14.95                          | <a href="#">Source</a> |                        |
| IWI16                              | Mineral wool                                                                                       | 50-200 mm metal support<br>50-200 mm mineral wool<br>12.5 mm vapour barrier + plasterboard | 0.060866667         | <input checked="" type="checkbox"/> | 50                            | 2419                              | 0.0007481                            | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 50                                | 200                               | 50                          | 66.97                           | 2.1758                             | <a href="#">Source</a> | 1                      | 50                      | 2.3068                      | 0.9902                         | <a href="#">Source</a> |                        |
| IWI17                              | Perlite insulation board                                                                           | 10 mm light mineral mortar<br>50-100 expanded perlite<br>10 mm interior plaster            | 10                  | <input type="checkbox"/>            | 50                            | 0.564                             | 0.0169                               | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 50                                | 100                               | 50                          | 534.9                           | 19.47                              | <a href="#">Source</a> | 0.01                   | 50                      | 203.2                       | 14.95                          | <a href="#">Source</a> |                        |
| IWI18                              | Phenolic foam boards                                                                               | 10 mm glue mortar<br>20-200 mm phenolic foam board<br>10 mm interior plaster               | 150                 | <input type="checkbox"/>            | 50                            | 8.045                             | 2.21                                 | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 20                                | 200                               | 50                          | 94.38                           | 90.84                              | <a href="#">Source</a> | 0.01                   | 50                      | 203.2                       | 14.95                          | <a href="#">Source</a> |                        |
| IWI19                              | Polystyrol/EPS/XPS                                                                                 | 10 mm gypsum mortar<br>50-140 mm polystyrene board<br>12.5 mm plasterboard                 | 10.5                | <input type="checkbox"/>            | 50                            | 0.144                             | 0.015                                | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 50                                | 140                               | 50                          | 58.61                           | 50.4                               | <a href="#">Source</a> | 1                      | 50                      | 1.708                       | 0.7705                         | <a href="#">Source</a> |                        |
| IWI20                              | Polyurethane insulation (PIR/PUR)                                                                  | 10 mm glue mortar<br>20-200 mm polyurethane insulation<br>12.5 mm plasterboard             | 150                 | <input type="checkbox"/>            | 50                            | 8.045                             | 2.21                                 | <a href="#">Source</a>   | 0.000833          | <input checked="" type="checkbox"/> | 20                                | 200                               | 50                          | 14.37                           | 8.644                              | <a href="#">Source</a> | 1                      | 50                      | 1.708                       | 0.7705                         | <a href="#">Source</a> |                        |
| IWI21                              | PU-foam with calciumsilicate channels                                                              | 10 mm glue mortar<br>30-120 mm iQ Therm<br>10 mm interior plaster                          | 150                 | <input type="checkbox"/>            | 50                            | 8.045                             | 2.21                                 | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 30                                | 120                               | 50                          | 176                             | 0.05752                            | <a href="#">Source</a> | 0.01                   | 50                      | 203.2                       | 14.95                          | <a href="#">Source</a> |                        |
| IWI23                              | Reed insulation                                                                                    | 30-110 mm timber construction<br>30-110 mm reed insulation<br>10 mm lime plaster           | 0.0001              | <input checked="" type="checkbox"/> | 50                            | -629.4                            | 863                                  | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 30                                | 110                               | 50                          | -182                            | 87.7                               | <a href="#">Source</a> | 0.01                   | 50                      | 193.9                       | 14.95                          | <a href="#">Source</a> |                        |
| IWI25                              | Thermal insulation glazing                                                                         | 100 mm thermal glazing with metal structure                                                |                     | <input type="checkbox"/>            |                               |                                   |                                      |                          | 1                 | <input type="checkbox"/>            |                                   |                                   |                             | 50                              | 124.1                              | 6.6602                 | <a href="#">Source</a> |                         |                             |                                |                        |                        |

| Solution ID                        | Solution Name                              | Build-up Description                                                                        | Substructure Factor | Substructure is Variable?           | Substructure Lifespan [Years] | Substructure Embodied GHG (A1-A3) | Substructure End-of-Life GHG (C3-C4) | Substructure Data Source | Insulation Factor | Insulation is Variable?             | Insulation Minimum Thickness [mm] | Insulation Maximum Thickness [mm] | Insulation Lifespan [Years] | Insulation Embodied GHG (A1-A3) | Insulation End-of-Life GHG (C3-C4) | Insulation Data Source | Finish Factor | Finish Lifespan [Years] | Finish Embodied GHG (A1-A3) | Finish End-of-Life GHG (C3-C4) | Finish Data Source     |
|------------------------------------|--------------------------------------------|---------------------------------------------------------------------------------------------|---------------------|-------------------------------------|-------------------------------|-----------------------------------|--------------------------------------|--------------------------|-------------------|-------------------------------------|-----------------------------------|-----------------------------------|-----------------------------|---------------------------------|------------------------------------|------------------------|---------------|-------------------------|-----------------------------|--------------------------------|------------------------|
| IWI26                              | Thermal insulation plaster                 | 50-80 mm thermal insulating plaster                                                         |                     | <input type="checkbox"/>            |                               |                                   |                                      |                          | 0.6               | <input checked="" type="checkbox"/> | 50                                | 80                                | 50                          | 0.964                           | 0.081                              | <a href="#">Source</a> |               |                         |                             |                                |                        |
| IWI28                              | Vacuum Insulation Panel (VIP)              | 10 mm glue mortar<br>20-50 mm Vacuum Insulation Panel<br>12,5 plasterboard                  | 150                 | <input type="checkbox"/>            | 50                            | 8.045                             | 2.21                                 | <a href="#">Source</a>   | 0.05              | <input checked="" type="checkbox"/> | 20                                | 50                                | 50                          | 17.8                            | 0.0225                             | <a href="#">Source</a> | 1             | 50                      | 1.708                       | 0.7705                         | <a href="#">Source</a> |
| IWI29                              | Ventilated interior insulation (RetroWall) | 25 mm metal support<br>50 mm mineral wool<br>12,5 vapour barrier + plasterboard             |                     | <input type="checkbox"/>            |                               |                                   |                                      |                          | 0.05              | <input type="checkbox"/>            |                                   |                                   | 50                          | 66.97                           | 2.1758                             | <a href="#">Source</a> | 1             | 50                      | 2.3068                      | 0.9902                         | <a href="#">Source</a> |
| IWI30                              | Wood fibre board                           | Steel screws<br>40-200 wood fibre board<br>12,5 mm plasterboard                             | 0.006153846         | <input checked="" type="checkbox"/> | 50                            | 4183                              | 0.0007481                            | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 40                                | 200                               | 50                          | -174.8                          | 258.4                              | <a href="#">Source</a> | 1             | 50                      | 1.708                       | 0.7705                         | <a href="#">Source</a> |
| IWI31                              | Wood fibre board with vapour control layer | Steel screws<br>40-100 wood fibre board with control layer<br>12,5 mm plasterboard          | 0.006153846         | <input checked="" type="checkbox"/> | 50                            | 4183                              | 0.0007481                            | <a href="#">Source</a>   | 0.01              | <input checked="" type="checkbox"/> | 40                                | 100                               | 60                          | 16.3                            | 3.27                               | <a href="#">Source</a> | 1             | 50                      | 1.708                       | 0.7705                         | <a href="#">Source</a> |
| External Wall Insulation solutions |                                            |                                                                                             |                     |                                     |                               |                                   |                                      |                          |                   |                                     |                                   |                                   |                             |                                 |                                    |                        |               |                         |                             |                                |                        |
| EW11                               | Aerogel insulating plaster                 | 45-100 mm aerogel insulating plaster                                                        |                     | <input type="checkbox"/>            |                               |                                   |                                      |                          | 0.22              | <input checked="" type="checkbox"/> | 45                                | 100                               | 40                          | 4.39                            | 0.00467                            | <a href="#">Source</a> |               |                         |                             |                                |                        |
| EW12                               | Cavity wall insulation with insulation     | 90-500 mm loose mineral wool fibre                                                          |                     | <input type="checkbox"/>            |                               |                                   |                                      |                          | 0.001             | <input checked="" type="checkbox"/> | 90                                | 500                               | 50                          | 64.89                           | 2.1368                             | <a href="#">Source</a> |               |                         |                             |                                |                        |
| EW13                               | Cellulose in timber frame                  | 160-280 mm timber construction<br>160-280 mm cellulose<br>30 mm wood cladding               | 0.0001              | <input checked="" type="checkbox"/> | 50                            | -629.4                            | 863                                  | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 160                               | 280                               | 50                          | -72.72                          | 84.14                              | <a href="#">Source</a> | 0.03          | 50                      | -196.4                      | 760.1                          | <a href="#">Source</a> |
| EW14                               | Foam glass                                 | 10 mm glue<br>40-200 mm foam glass board<br>10 mm external plaster                          | 4                   | <input type="checkbox"/>            | 50                            | 0.8554                            | 0.03844                              | <a href="#">Source</a>   | 0.165             | <input checked="" type="checkbox"/> | 40                                | 200                               | 50                          | 2.391                           | 0.01963                            | <a href="#">Source</a> | 0.01          | 50                      | 344.892976                  | 40.4540625                     | <a href="#">Source</a> |
| EW15                               | Hemp insulation board                      | 40-180 mm timber construction<br>40-180 mm hemp insulation board<br>10 mm external plaster  | 0.0001              | <input checked="" type="checkbox"/> | 50                            | -629.4                            | 863                                  | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 40                                | 180                               | 50                          | 58.2580504                      | 75.4781615                         | <a href="#">Source</a> | 0.01          | 50                      | 344.892976                  | 40.4540625                     | <a href="#">Source</a> |
| EW16                               | Insulation cork boards                     | Steel screws<br>50-300 mm cork insulation<br>10 mm external plaster                         | 0.006153846         | <input checked="" type="checkbox"/> | 50                            | 4183                              | 0.0007481                            | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 50                                | 300                               | 50                          | -85.08                          | 128.3                              | <a href="#">Source</a> | 0.01          | 50                      | 344.892976                  | 40.4540625                     | <a href="#">Source</a> |
| EW17                               | Mineral insulation boards                  | 10 mm light mineral mortar<br>60-300 mm mineral insulation boards<br>10 mm external plaster | 10                  | <input type="checkbox"/>            | 50                            | 0.564                             | 0.0169                               | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 60                                | 300                               | 50                          | 174.5                           | 6.065                              | <a href="#">Source</a> | 0.01          | 50                      | 344.892976                  | 40.4540625                     | <a href="#">Source</a> |
| EW18                               | Mineral wool insulation                    | 60-400 mm timber construction<br>60-400 mm mineral wool<br>30 mm wood cladding              | 0.0001              | <input checked="" type="checkbox"/> | 50                            | -629.4                            | 863                                  | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 60                                | 400                               | 50                          | 66.97                           | 2.1758                             | <a href="#">Source</a> | 0.03          | 50                      | -196.4                      | 760.1                          | <a href="#">Source</a> |
| EW19                               | Phenolic foam boards                       | 10 mm glue<br>20-200 mm phenolic foam board<br>10 mm external plaster                       | 4                   | <input type="checkbox"/>            | 50                            | 0.8554                            | 0.03844                              | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 20                                | 200                               | 50                          | 94.37904                        | 90.8419665                         | <a href="#">Source</a> | 0.01          | 50                      | 344.892976                  | 40.4540625                     | <a href="#">Source</a> |
| EW110                              | Polystyrol insulation (EPS/XPS)            | 10 mm light mineral mortar<br>20-400 EPS/XPS board<br>10 mm external plaster                | 10                  | <input type="checkbox"/>            | 50                            | 0.564                             | 0.0169                               | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 20                                | 400                               | 50                          | 58.61                           | 50.4                               | <a href="#">Source</a> | 0.01          | 50                      | 344.892976                  | 40.4540625                     | <a href="#">Source</a> |
| EW111                              | Polyurethane insulation (PIR/PUR)          | 10 mm glue<br>20-300 mm PU board<br>10 mm external plaster                                  | 4                   | <input type="checkbox"/>            | 50                            | 0.8554                            | 0.03844                              | <a href="#">Source</a>   | 0.000833          | <input checked="" type="checkbox"/> | 20                                | 300                               | 50                          | 14.37                           | 8.644                              | <a href="#">Source</a> | 0.01          | 50                      | 344.892976                  | 40.4540625                     | <a href="#">Source</a> |
| EW114                              | Thermal insulating plaster                 | 30-120 mm thermal insulating plaster                                                        |                     | <input type="checkbox"/>            |                               |                                   |                                      |                          | 0.6               | <input checked="" type="checkbox"/> | 30                                | 120                               | 50                          | 0.964                           | 0.081                              | <a href="#">Source</a> |               |                         |                             |                                |                        |
| EW115                              | Vacuum Insulation Panels (VIP)             | 10 mm glue<br>20-50 mm vacuum panel<br>30 mm glass wool + 30 mm wood cladding               | 4                   | <input type="checkbox"/>            | 50                            | 0.8554                            | 0.03844                              | <a href="#">Source</a>   | 0.05              | <input checked="" type="checkbox"/> | 20                                | 50                                | 50                          | 17.8                            | 0.0225                             | <a href="#">Source</a> | 1             | 50                      | -3946.16576                 | 228.682642                     | <a href="#">Source</a> |
| EW116                              | Wood fibre/wood wool insulation            | 100-200 mm timber construction<br>100-200 wood fibre insulation<br>30 mm wood cladding      | 0.0001              | <input checked="" type="checkbox"/> | 50                            | -629.4                            | 863                                  | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 100                               | 200                               | 50                          | -174.8                          | 258.4                              | <a href="#">Source</a> | 0.03          | 50                      | -196.4                      | 760.1                          | <a href="#">Source</a> |
| Roof Insulation solutions          |                                            |                                                                                             |                     |                                     |                               |                                   |                                      |                          |                   |                                     |                                   |                                   |                             |                                 |                                    |                        |               |                         |                             |                                |                        |
| RI1                                | Blown-in cellulose in attic                | 100-500 mm blow-in cellulose<br>20 mm wooden flooring                                       |                     | <input type="checkbox"/>            |                               |                                   |                                      |                          | 0.001             | <input checked="" type="checkbox"/> | 100                               | 500                               | 50                          | -72.72                          | 84.14                              | <a href="#">Source</a> | 0.02          | 50                      | -196.4                      | 760.1                          | <a href="#">Source</a> |
| RI2                                | Clay boards                                | Steel screws<br>20 mm clay panel<br>10 mm clay plaster                                      | 0.123076923         | <input type="checkbox"/>            | 50                            | 4183                              | 0.0007481                            | <a href="#">Source</a>   | 1                 | <input type="checkbox"/>            |                                   |                                   | 50                          | 0.6423                          | 1.824                              | <a href="#">Source</a> | 0.01          | 50                      | 100.1                       | 2.601                          | <a href="#">Source</a> |

| Solution ID                                  | Solution Name                                                     | Build-up Description                                                                        | Substructure Factor | Substructure is Variable?           | Substructure Lifespan [Years] | Substructure Embodied GHG (A1-A3) | Substructure End-of-Life GHG (C3-C4) | Substructure Data Source | Insulation Factor | Insulation is Variable?             | Insulation Minimum Thickness [mm] | Insulation Maximum Thickness [mm] | Insulation Lifespan [Years] | Insulation Embodied GHG (A1-A3) | Insulation End-of-Life GHG (C3-C4) | Insulation Data Source | Finish Factor          | Finish Lifespan [Years] | Finish Embodied GHG (A1-A3) | Finish End-of-Life GHG (C3-C4) | Finish Data Source     |                        |
|----------------------------------------------|-------------------------------------------------------------------|---------------------------------------------------------------------------------------------|---------------------|-------------------------------------|-------------------------------|-----------------------------------|--------------------------------------|--------------------------|-------------------|-------------------------------------|-----------------------------------|-----------------------------------|-----------------------------|---------------------------------|------------------------------------|------------------------|------------------------|-------------------------|-----------------------------|--------------------------------|------------------------|------------------------|
| RI3                                          | Construction wood + cellulose                                     | 100-300 mm cellulose within structure<br>12,5 finish board                                  |                     | <input type="checkbox"/>            |                               |                                   |                                      |                          | 0.00085           | <input checked="" type="checkbox"/> | 100                               | 300                               | 50                          | -72.72                          | 84.14                              | <a href="#">Source</a> | 1                      | 50                      | 1.708                       | 0.7705                         | <a href="#">Source</a> |                        |
| RI4                                          | Construction wood + mineral wool/glass wool/rock wool             | 100-300 mm mineral wool within structure<br>12,5 mm finish board                            |                     | <input type="checkbox"/>            |                               |                                   |                                      |                          | 0.001             | <input checked="" type="checkbox"/> | 100                               | 300                               | 50                          | 191.6                           | 2.632                              | <a href="#">Source</a> | 1                      | 50                      | 1.708                       | 0.7705                         | <a href="#">Source</a> |                        |
| RI5                                          | Construction wood + plant fiber insulation                        | 100-300 mm plant fiber insulation within structure<br>12,5 finish board                     |                     | <input type="checkbox"/>            |                               |                                   |                                      |                          | 0.034             | <input checked="" type="checkbox"/> | 100                               | 300                               | 50                          | -0.7154                         | 1.631                              | <a href="#">Source</a> | 1                      | 50                      | 1.708                       | 0.7705                         | <a href="#">Source</a> |                        |
| RI12                                         | Mineral wool/glass wool/rock wool (loose/blown-in)                | 100-300 mm loose mineral wool<br>12,5 finish board                                          |                     | <input type="checkbox"/>            |                               |                                   |                                      |                          | 0.001             | <input checked="" type="checkbox"/> | 100                               | 300                               | 50                          | 64.89                           | 2.1368                             | <a href="#">Source</a> | 1                      | 50                      | 1.708                       | 0.7705                         | <a href="#">Source</a> |                        |
| Basement and Foundation Insulation solutions |                                                                   |                                                                                             |                     |                                     |                               |                                   |                                      |                          |                   |                                     |                                   |                                   |                             |                                 |                                    |                        |                        |                         |                             |                                |                        |                        |
| BF1                                          | Aerogel composite panel on the floor                              | Steel screws<br>10 mm aerogel blanket<br>20 mm wooden flooring                              | 0.051282051         | <input type="checkbox"/>            | 50                            | 4183                              | 0.0007481                            | <a href="#">Source</a>   | 1                 | <input type="checkbox"/>            |                                   |                                   |                             | 50                              | 12.8                               | 0                      | <a href="#">Source</a> | 0.02                    | 50                          | -196.4                         | 760.1                  | <a href="#">Source</a> |
| BF12                                         | Blown-in cellulose                                                | 100-300 mm blown in cellulose<br>20 mm wooden flooring                                      |                     | <input type="checkbox"/>            |                               |                                   |                                      |                          | 0.001             | <input checked="" type="checkbox"/> | 100                               | 300                               | 50                          | -72.72                          | 84.14                              | <a href="#">Source</a> | 0.02                   | 50                      | -196.4                      | 760.1                          | <a href="#">Source</a> |                        |
| BF13                                         | External insulation on foundation: EPS/XPS                        | 10 mm light mineral mortar<br>20-400 EPS/XPS board<br>10 mm external plaster                | 10                  | <input type="checkbox"/>            | 50                            | 0.564                             | 0.0169                               | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 20                                | 400                               | 50                          | 58.61                           | 50.4                               | <a href="#">Source</a> | 0.01                   | 50                      | 344.892976                  | 40.4540625                     | <a href="#">Source</a> |                        |
| BF14                                         | External insulation on foundation: foam glass                     | 10 mm glue<br>40-200 mm foam glass board<br>10 mm external plaster                          | 4                   | <input type="checkbox"/>            | 50                            | 0.8554                            | 0.03844                              | <a href="#">Source</a>   | 0.165             | <input checked="" type="checkbox"/> | 40                                | 200                               | 50                          | 2.391                           | 0.01963                            | <a href="#">Source</a> | 0.01                   | 50                      | 344.892976                  | 40.4540625                     | <a href="#">Source</a> |                        |
| BF15                                         | External insulation on foundation: mineral boards                 | 10 mm light mineral mortar<br>60-300 mm mineral insulation boards<br>10 mm external plaster | 10                  | <input type="checkbox"/>            | 50                            | 0.564                             | 0.0169                               | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 60                                | 300                               | 50                          | 174.5                           | 6.065                              | <a href="#">Source</a> | 0.01                   | 50                      | 344.892976                  | 40.4540625                     | <a href="#">Source</a> |                        |
| BF16                                         | External insulation on foundation: Vacuum Insulation Panels (VIP) | 10 mm glue<br>20-50 mm vacuum panel<br>30 mm glass wool + 30 mm wood cladding               | 4                   | <input type="checkbox"/>            | 50                            | 0.8554                            | 0.03844                              | <a href="#">Source</a>   | 0.05              | <input checked="" type="checkbox"/> | 20                                | 50                                | 50                          | 17.8                            | 0.0225                             | <a href="#">Source</a> | 1                      | 50                      | -3946.16576                 | 228.682642                     | <a href="#">Source</a> |                        |
| BF17                                         | Foam glass on the floor                                           | 50-500 mm mm vacuum panel<br>80 mm concrete screed + 20 mm flooring                         |                     | <input type="checkbox"/>            |                               |                                   |                                      |                          | 0.165             | <input checked="" type="checkbox"/> | 50                                | 500                               | 50                          | 2.391                           | 0.01963                            | <a href="#">Source</a> | 1                      | 50                      | 31.592                      | 18.39112                       | <a href="#">Source</a> |                        |
| BF113                                        | Mineral wool under the ceiling                                    | Steel screws<br>50-500 mm mineral wool<br>12,5 mm finish board                              | 0.006153846         | <input checked="" type="checkbox"/> | 50                            | 4183                              | 0.0007481                            | <a href="#">Source</a>   | 0.001             | <input checked="" type="checkbox"/> | 50                                | 500                               | 50                          | 34.49                           | 1.517                              | <a href="#">Source</a> | 1                      | 50                      | 1.708                       | 0.7705                         | <a href="#">Source</a> |                        |

## 12.7. LCA calculator – windows database

The following is the database used for LCA calculator for windows solutions, in its current completeness.

| Solution ID | Glazing Factor | Glazing<br>Lifespan<br>[Years] | Glazing<br>Embodied<br>GHG (A1-A3) | Glazing End-of-<br>Life GHG (C3-<br>C4) | Glazing Data Source                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Frame Factor | Frame<br>Lifespan<br>[Years] | Frame<br>Embodied<br>GHG (A1-A3) | Frame End-<br>of-Life GHG<br>(C3-C4) | Frame Data Source                                       | Coats/Sealings<br>Factor | Coats/Sealings<br>Lifespan [Years] | Coats/Sealings<br>Embodied GHG<br>(A1-A3) | Coats/Sealings<br>End-of-Life<br>GHG (C3-C4) | Coats/Sealings Data Source                                                                                                                                                              |
|-------------|----------------|--------------------------------|------------------------------------|-----------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|------------------------------|----------------------------------|--------------------------------------|---------------------------------------------------------|--------------------------|------------------------------------|-------------------------------------------|----------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1A0v        |                |                                |                                    |                                         |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 1.11374408   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                                                                                                                                                                                         |
| 1B1a        |                |                                |                                    |                                         |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 1.11374408   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 2.977367612              | 20                                 | 0.0728                                    | 0.0472                                       | <a href="https://dafa-build.com/media/yx3lly2z/epd_dafa_a_s_dafa_qlon_hub-0957_2024-01-03.pdf">https://dafa-build.com/media/yx3lly2z/epd_dafa_a_s_dafa_qlon_hub-0957_2024-01-03.pdf</a> |
| 1B3a        |                |                                |                                    |                                         |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 1.67061611   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 2.977367612              | 20                                 | 0.0728                                    | 0.0472                                       | <a href="https://dafa-build.com/media/yx3lly2z/epd_dafa_a_s_dafa_qlon_hub-0957_2024-01-03.pdf">https://dafa-build.com/media/yx3lly2z/epd_dafa_a_s_dafa_qlon_hub-0957_2024-01-03.pdf</a> |
| 1B4a        |                |                                |                                    |                                         |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 2.78436019   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 2.977367612              | 20                                 | 0.0728                                    | 0.0472                                       | <a href="https://dafa-build.com/media/yx3lly2z/epd_dafa_a_s_dafa_qlon_hub-0957_2024-01-03.pdf">https://dafa-build.com/media/yx3lly2z/epd_dafa_a_s_dafa_qlon_hub-0957_2024-01-03.pdf</a> |
| 1C1b        | 1              | 12                             | 5.63                               | 0.1378                                  | <a href="https://www.environdec.com/library/epd6663">https://www.environdec.com/library/epd6663</a>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 1.11374408   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                                                                                                                                                                                         |
| 1C4b        | 1              | 12                             | 5.63                               | 0.1378                                  | <a href="https://www.environdec.com/library/epd6663">https://www.environdec.com/library/epd6663</a>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 2.78436019   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                                                                                                                                                                                         |
| 2A3h        | 1              | 50                             | 35                                 | 0.0422                                  | <a href="https://www.fineoglass.eu/wp-content/uploads/47/20260227_EPd_NMD_FINE_O_8_Standard.pdf">https://www.fineoglass.eu/wp-content/uploads/47/20260227_EPd_NMD_FINE_O_8_Standard.pdf</a>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 1.67061611   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                                                                                                                                                                                         |
| 2A4d        | 1              | 30                             | 38.28                              | 1.8774                                  | <a href="https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=d7bf4202-d1a8-4f3e-8861-c3d78cd2bf70&amp;version=20.24.070&amp;lang=en">https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=d7bf4202-d1a8-4f3e-8861-c3d78cd2bf70&amp;version=20.24.070&amp;lang=en</a>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | 2.78436019   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                                                                                                                                                                                         |
| 2A4e        | 1              | 30                             | 24.72                              | 2.8488                                  | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT ( <a href="https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=d7bf4202-d1a8-4f3e-8861-c3d78cd2bf70&amp;version=20.24.070&amp;lang=en">https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=d7bf4202-d1a8-4f3e-8861-c3d78cd2bf70&amp;version=20.24.070&amp;lang=en</a> )<br><b>MINUS</b> Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT ( <a href="https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&amp;version=20.24.070&amp;lang=de">https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&amp;version=20.24.070&amp;lang=de</a> ) | 2.78436019   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                                                                                                                                                                                         |
| 2A4g        | 1              | 30                             | 39.42                              | 3.2942                                  | Process Data set: Insulated glazing, triple pane; 31 kg/m2 (en) - OEKOBAU.DAT ( <a href="https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=ba58d8b9-945b-4428-b4e0-aecda8b3df18&amp;version=20.24.070&amp;lang=en">https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=ba58d8b9-945b-4428-b4e0-aecda8b3df18&amp;version=20.24.070&amp;lang=en</a> )<br><b>MINUS</b> Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT ( <a href="https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&amp;version=20.24.070&amp;lang=de">https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&amp;version=20.24.070&amp;lang=de</a> )     | 2.78436019   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                                                                                                                                                                                         |
| 2A4h        | 1              | 50                             | 35                                 | 0.0422                                  | 20260227_EPd_NMD_FINEO_8_Standard.pdf                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 2.78436019   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                                                                                                                                                                                         |

| Solution ID | Glazing Factor | Glazing<br>Lifespan<br>[Years] | Glazing<br>Embodied<br>GHG (A1-A3) | Glazing End-of-<br>Life GHG (C3-<br>C4) | Glazing Data Source                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Frame Factor | Frame<br>Lifespan<br>[Years] | Frame<br>Embodied<br>GHG (A1-A3) | Frame End-<br>of-Life GHG<br>(C3-C4) | Frame Data Source                                       | Coats/Sealings<br>Factor | Coats/Sealings<br>Lifespan [Years] | Coats/Sealings<br>Embodied GHG<br>(A1-A3) | Coats/Sealings<br>End-of-Life<br>GHG (C3-C4) | Coats/Sealings Data Source                                                      |
|-------------|----------------|--------------------------------|------------------------------------|-----------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|------------------------------|----------------------------------|--------------------------------------|---------------------------------------------------------|--------------------------|------------------------------------|-------------------------------------------|----------------------------------------------|---------------------------------------------------------------------------------|
| 2C1d        | 1              | 30                             | 38.28                              | 1.8774                                  | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                         | 6.68246445   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.054932982              | 50                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 2C1i        | 4              | 30                             | 3.381                              | 0.02786                                 | Process Data set: Glass - Guardian Europe S.à r.l. - Coated flat glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                 | 1.11374408   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.054932982              | 50                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 2C1j        | 1              | 50                             | 35                                 | 0.0422                                  | 20260227_EPD_NMD_FINEO_8_Standard.pdf                                                                                                                                                                                                                                                                                                                                                                                                                                     | 1.11374408   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.054932982              | 50                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 2C2i        | 4              | 30                             | 3.381                              | 0.02786                                 | Process Data set: Glass - Guardian Europe S.à r.l. - Coated flat glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                 | 1.7535545    | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.054932982              | 50                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 2C3i        | 4              | 30                             | 3.381                              | 0.02786                                 | Process Data set: Glass - Guardian Europe S.à r.l. - Coated flat glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                 | 1.67061611   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.054932982              | 50                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 2C4i        | 4              | 30                             | 3.381                              | 0.02786                                 | Process Data set: Glass - Guardian Europe S.à r.l. - Coated flat glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                 | 2.78436019   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.054932982              | 50                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 2D1m        | 1              | 30                             | 38.28                              | 1.8774                                  | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                         | 17.535545    | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.549329818              | 30                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 2D1n        | 1              | 30                             | 59.76                              | 3.5736                                  | Process Data set: Insulated glazing, triple pane; 31 kg/m2 (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                             | 25.8293839   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.549329818              | 30                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 2D2m        | 1              | 30                             | 38.28                              | 1.8774                                  | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                         | 17.535545    | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.549329818              | 30                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 2D3m        | 1              | 30                             | 38.28                              | 1.8774                                  | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                         | 17.535545    | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.549329818              | 30                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 2E4m        | 1              | 30                             | 38.28                              | 1.8774                                  | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                         | 8.76777251   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                                                                                 |
| 2E4n        | 1              | 30                             | 59.76                              | 3.5736                                  | Process Data set: Insulated glazing, triple pane; 31 kg/m2 (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                             | 12.9146919   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                                                                                 |
| 3A1c        | 4              | 30                             | 3.381                              | 0.02786                                 | Process Data set: Glass - Guardian Europe S.à r.l. - Coated flat glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                 | 1.11374408   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                                                                                 |
| 3A1d        | 1              | 30                             | 38.28                              | 1.8774                                  | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                         | 1.11374408   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                                                                                 |
| 3A1e        | 1              | 30                             | 24.72                              | 2.8488                                  | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT<br>(https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=d7bf4202-d1a8-4f3e-8861-c3d78cd2bf70&version=20.24.070&lang=en)<br><b>MINUS</b> Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT<br>(https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&version=20.24.070&lang=de) | 1.7535545    | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                                                                                 |

| Solution ID | Glazing Factor | Glazing<br>Lifespan<br>[Years] | Glazing<br>Embodied<br>GHG (A1-A3) | Glazing End-of-<br>Life GHG (C3-<br>C4) | Glazing Data Source                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Frame Factor | Frame<br>Lifespan<br>[Years] | Frame<br>Embodied<br>GHG (A1-A3) | Frame End-<br>of-Life GHG<br>(C3-C4) | Frame Data Source                                       | Coats/Sealings<br>Factor | Coats/Sealings<br>Lifespan [Years] | Coats/Sealings<br>Embodied GHG<br>(A1-A3) | Coats/Sealings<br>End-of-Life<br>GHG (C3-C4) | Coats/Sealings Data Source |
|-------------|----------------|--------------------------------|------------------------------------|-----------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|------------------------------|----------------------------------|--------------------------------------|---------------------------------------------------------|--------------------------|------------------------------------|-------------------------------------------|----------------------------------------------|----------------------------|
| 3A1g        | 1              | 30                             | 39.42                              | 3.2942                                  | Process Data set: Insulated glazing, triple pane;<br>31 kg/m2 (en) - OEKOBAU.DAT<br>( <a href="https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=ba58d8b9-945b-4428-b4e0-aecda8b3df18&amp;version=20.24.070&amp;lang=en">https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=ba58d8b9-945b-4428-b4e0-aecda8b3df18&amp;version=20.24.070&amp;lang=en</a> )<br><b>MINUS</b> Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT<br>( <a href="https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&amp;version=20.24.070&amp;lang=de">https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&amp;version=20.24.070&amp;lang=de</a> )  | 1.7535545    | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                            |
| 3A1h        | 1              | 50                             | 35                                 | 0.0422                                  | 20260227_EPD_NMD_FINEO_8_Standard.pdf                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 1.11374408   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                            |
| 3A3f        | 1              | 30                             | 59.76                              | 3.5736                                  | Process Data set: Insulated glazing, triple pane;<br>31 kg/m2 (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 1.67061611   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                            |
| 3A3f        | 1              | 30                             | 38.28                              | 1.8774                                  | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 1.67061611   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                            |
| 3A4c        | 4              | 30                             | 3.381                              | 0.02786                                 | Process Data set: Glass - Guardian Europe S.à r.l. - Coated flat glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 2.78436019   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                            |
| 3A4d        | 1              | 30                             | 38.28                              | 1.8774                                  | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 2.78436019   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                            |
| 3A4e        | 1              | 30                             | 24.72                              | 2.8488                                  | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT<br>( <a href="https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=d7bf4202-d1a8-4f3e-8861-c3d78cd2bf70&amp;version=20.24.070&amp;lang=en">https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=d7bf4202-d1a8-4f3e-8861-c3d78cd2bf70&amp;version=20.24.070&amp;lang=en</a> )<br><b>MINUS</b> Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT<br>( <a href="https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&amp;version=20.24.070&amp;lang=de">https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&amp;version=20.24.070&amp;lang=de</a> ) | 2.78436019   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                            |
| 3A4g        | 1              | 30                             | 39.42                              | 3.2942                                  | Process Data set: Insulated glazing, triple pane;<br>31 kg/m2 (en) - OEKOBAU.DAT<br>( <a href="https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=ba58d8b9-945b-4428-b4e0-aecda8b3df18&amp;version=20.24.070&amp;lang=en">https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=ba58d8b9-945b-4428-b4e0-aecda8b3df18&amp;version=20.24.070&amp;lang=en</a> )<br><b>MINUS</b> Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT<br>( <a href="https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&amp;version=20.24.070&amp;lang=de">https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&amp;version=20.24.070&amp;lang=de</a> )  | 2.78436019   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                            |
| 3A4h        | 1              | 50                             | 35                                 | 0.0422                                  | 20260227_EPD_NMD_FINEO_8_Standard.pdf                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 2.78436019   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                          |                                    |                                           |                                              |                            |

| Solution ID | Glazing Factor | Glazing<br>Lifespan<br>[Years] | Glazing<br>Embodied<br>GHG (A1-A3) | Glazing End-of-<br>Life GHG (C3-<br>C4) | Glazing Data Source | Frame Factor                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Frame<br>Lifespan<br>[Years] | Frame<br>Embodied<br>GHG (A1-A3) | Frame End-<br>of-Life GHG<br>(C3-C4) | Frame Data Source | Coats/Sealings<br>Factor                                | Coats/Sealings<br>Lifespan [Years] | Coats/Sealings<br>Embodied GHG<br>(A1-A3) | Coats/Sealings<br>End-of-Life<br>GHG (C3-C4) | Coats/Sealings Data Source                                                      |
|-------------|----------------|--------------------------------|------------------------------------|-----------------------------------------|---------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------|----------------------------------|--------------------------------------|-------------------|---------------------------------------------------------|------------------------------------|-------------------------------------------|----------------------------------------------|---------------------------------------------------------------------------------|
| 3B1k        |                | 1                              | 50                                 | 13.56                                   | 0.1812              | Prozess-Datensatz: Fensterglas einfach (de) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 11.1374408                   | 30                               | -0.1773                              | 3.988             | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.549329818                        | 30                                        | 9.229                                        | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 3B1l        |                | 4                              | 30                                 | 3.381                                   | 0.02786             | Process Data set: Glass - Guardian Europe S.à r.l. - Coated flat glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 11.1374408                   | 30                               | -0.1773                              | 3.988             | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.549329818                        | 30                                        | 9.229                                        | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 3B1m        |                | 1                              | 30                                 | 38.28                                   | 1.8774              | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 17.535545                    | 30                               | -0.1773                              | 3.988             | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.549329818                        | 30                                        | 9.229                                        | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 3B1n        |                | 1                              | 30                                 | 59.76                                   | 3.5736              | Process Data set: Insulated glazing, triple pane; 31 kg/m2 (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 25.8293839                   | 30                               | -0.1773                              | 3.988             | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.549329818                        | 30                                        | 9.229                                        | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 3C4m        |                | 1                              | 30                                 | 38.28                                   | 1.8774              | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 8.76777251                   | 30                               | -0.1773                              | 3.988             | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                                    |                                           |                                              |                                                                                 |
| 3C4n        |                | 1                              | 30                                 | 59.76                                   | 3.5736              | Process Data set: Insulated glazing, triple pane; 31 kg/m2 (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 12.9146919                   | 30                               | -0.1773                              | 3.988             | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT |                                    |                                           |                                              |                                                                                 |
| 4A1o        |                | 1                              | 30                                 | 24.72                                   | 2.8488              | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT<br>( <a href="https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=d7bf4202-d1a8-4f3e-8861-c3d78cd2bf70&amp;version=20.24.070&amp;lang=en">https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=d7bf4202-d1a8-4f3e-8861-c3d78cd2bf70&amp;version=20.24.070&amp;lang=en</a> )<br><b>MINUS</b> Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT<br>( <a href="https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&amp;version=20.24.070&amp;lang=de">https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&amp;version=20.24.070&amp;lang=de</a> ) | 11.1374408                   | 30                               | -0.1773                              | 3.988             | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.549329818                        | 30                                        | 9.229                                        | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 4A1m        |                | 1                              | 30                                 | 38.28                                   | 1.8774              | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 17.535545                    | 30                               | -0.1773                              | 3.988             | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.549329818                        | 30                                        | 9.229                                        | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 4A1n        |                | 1                              | 30                                 | 59.76                                   | 3.5736              | Process Data set: Insulated glazing, triple pane; 31 kg/m2 (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 20.6635071                   | 30                               | -0.1773                              | 3.988             | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.549329818                        | 30                                        | 9.229                                        | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 4A1p        |                | 1                              | 30                                 | 39.42                                   | 3.2942              | Process Data set: Insulated glazing, triple pane; 31 kg/m2 (en) - OEKOBAU.DAT<br>( <a href="https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=ba58d8b9-945b-4428-b4e0-aecda8b3df18&amp;version=20.24.070&amp;lang=en">https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=ba58d8b9-945b-4428-b4e0-aecda8b3df18&amp;version=20.24.070&amp;lang=en</a> )<br><b>MINUS</b> Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT<br>( <a href="https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&amp;version=20.24.070&amp;lang=de">https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&amp;version=20.24.070&amp;lang=de</a> )     | 17.535545                    | 30                               | -0.1773                              | 3.988             | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.549329818                        | 30                                        | 9.229                                        | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 4A1q        |                | 1                              | 50                                 | 35                                      | 0.0422              | 20260227_EPD_NMD_FINEO_8_Standard.pdf                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 11.1374408                   | 30                               | -0.1773                              | 3.988             | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.549329818                        | 30                                        | 9.229                                        | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |

| Solution ID | Glazing Factor | Glazing<br>Lifespan<br>[Years] | Glazing<br>Embodied<br>GHG (A1-A3) | Glazing End-of-<br>Life GHG (C3-<br>C4) | Glazing Data Source                                                                                                                                                                                                                                                                                                                                                                                                                                                                | Frame Factor | Frame<br>Lifespan<br>[Years] | Frame<br>Embodied<br>GHG (A1-A3) | Frame End-<br>of-Life GHG<br>(C3-C4) | Frame Data Source                                       | Coats/Sealings<br>Factor | Coats/Sealings<br>Lifespan [Years] | Coats/Sealings<br>Embodied GHG<br>(A1-A3) | Coats/Sealings<br>End-of-Life<br>GHG (C3-C4) | Coats/Sealings Data Source                                                      |
|-------------|----------------|--------------------------------|------------------------------------|-----------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|------------------------------|----------------------------------|--------------------------------------|---------------------------------------------------------|--------------------------|------------------------------------|-------------------------------------------|----------------------------------------------|---------------------------------------------------------------------------------|
| 4A3r        | 1              | 30                             | 51.84                              | 1.6962                                  | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT<br>(https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=d7bf4202-d1a8-4f3e-8861-c3d78cd2bf70&version=20.24.070&lang=en)<br><b>PLUS</b> Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT<br>(https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&version=20.24.070&lang=de)           | 26.3033175   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.823994726              | 30                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 4A3t        | 1              | 30                             | 52.98                              | 3.483                                   | Process Data set: Insulated glazing, triple pane; 31 kg/m2 (en) - OEKOBAU.DAT<br>(https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=ba58d8b9-945b-4428-b4e0-aecda8b3df18&version=20.24.070&lang=en)<br><b>PLUS and MINUS 3/2</b> Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT<br>(https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&version=20.24.070&lang=de) | 26.3033175   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.823994726              | 30                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 4A4S        | 1              | 30                             | 51.84                              | 1.6962                                  | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT<br>(https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=d7bf4202-d1a8-4f3e-8861-c3d78cd2bf70&version=20.24.070&lang=en)<br><b>PLUS</b> Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT<br>(https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&version=20.24.070&lang=de)           | 35.07109     | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 1.098659635              | 30                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 4A4u        | 1              | 30                             | 52.98                              | 3.483                                   | Process Data set: Insulated glazing, triple pane; 31 kg/m2 (en) - OEKOBAU.DAT<br>(https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=ba58d8b9-945b-4428-b4e0-aecda8b3df18&version=20.24.070&lang=en)<br><b>PLUS and MINUS 3/2</b> Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT<br>(https://www.oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dcf38066-e336-46a7-b0a8-b2453dd2872d&version=20.24.070&lang=de) | 35.07109     | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 1.098659635              | 30                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 4B1m        | 1              | 30                             | 38.28                              | 1.8774                                  | Process Data set: Insulated glazing, double pane; double glass (en) - OEKOBAU.DAT                                                                                                                                                                                                                                                                                                                                                                                                  | 17.535545    | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) - OEKOBAU.DAT | 0.549329818              | 30                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für Doppelflügel Fenster (de) - OEKOBAU.DAT |

| Solution ID | Glazing Factor | Glazing<br>Lifespan<br>[Years] | Glazing<br>Embodied<br>GHG (A1-A3) | Glazing End-of-<br>Life GHG (C3-<br>C4) | Glazing Data Source                                                                  | Frame Factor | Frame<br>Lifespan<br>[Years] | Frame<br>Embodied<br>GHG (A1-A3) | Frame End-<br>of-Life GHG<br>(C3-C4) | Frame Data Source                                          | Coats/Sealings<br>Factor | Coats/Sealings<br>Lifespan [Years] | Coats/Sealings<br>Embodied GHG<br>(A1-A3) | Coats/Sealings<br>End-of-Life<br>GHG (C3-C4) | Coats/Sealings Data Source                                                         |
|-------------|----------------|--------------------------------|------------------------------------|-----------------------------------------|--------------------------------------------------------------------------------------|--------------|------------------------------|----------------------------------|--------------------------------------|------------------------------------------------------------|--------------------------|------------------------------------|-------------------------------------------|----------------------------------------------|------------------------------------------------------------------------------------|
| 4B1n        | 1              | 30                             | 59.76                              | 3.5736                                  | Process Data set: Insulated glazing, triple pane;<br>31 kg/m2 (en) - OEKOBAU.DAT     | 25.8293839   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) -<br>OEKOBAU.DAT | 0.549329818              | 30                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für<br>Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 4B2m        | 1              | 30                             | 38.28                              | 1.8774                                  | Process Data set: Insulated glazing, double<br>pane; double glass (en) - OEKOBAU.DAT | 17.535545    | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) -<br>OEKOBAU.DAT | 0.549329818              | 30                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für<br>Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 4B2n        | 1              | 30                             | 59.76                              | 3.5736                                  | Process Data set: Insulated glazing, triple pane;<br>31 kg/m2 (en) - OEKOBAU.DAT     | 25.8293839   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) -<br>OEKOBAU.DAT | 0.549329818              | 30                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für<br>Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 4B3m        | 1              | 30                             | 38.28                              | 1.8774                                  | Process Data set: Insulated glazing, double<br>pane; double glass (en) - OEKOBAU.DAT | 17.535545    | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) -<br>OEKOBAU.DAT | 0.549329818              | 30                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für<br>Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 4B3n        | 1              | 30                             | 59.76                              | 3.5736                                  | Process Data set: Insulated glazing, triple pane;<br>31 kg/m2 (en) - OEKOBAU.DAT     | 25.8293839   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) -<br>OEKOBAU.DAT | 0.549329818              | 30                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für<br>Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 4B4m        | 1              | 30                             | 38.28                              | 1.8774                                  | Process Data set: Insulated glazing, double<br>pane; double glass (en) - OEKOBAU.DAT | 17.535545    | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) -<br>OEKOBAU.DAT | 0.549329818              | 30                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für<br>Doppelflügel Fenster (de) - OEKOBAU.DAT |
| 4B4n        | 1              | 30                             | 59.76                              | 3.5736                                  | Process Data set: Insulated glazing, triple pane;<br>31 kg/m2 (en) - OEKOBAU.DAT     | 25.8293839   | 30                           | -0.1773                          | 3.988                                | Prozess-Datensatz: Holz-Flügelrahmen (de) -<br>OEKOBAU.DAT | 0.549329818              | 30                                 | 9.229                                     |                                              | Prozess-Datensatz: Fenster-Beschlag für<br>Doppelflügel Fenster (de) - OEKOBAU.DAT |

## 12.8. LCA calculator – active systems database

The following is the database used for LCA calculator for active systems solutions, in its current completeness.

| Solution name                                                              | Total embodied GHG (A1-A3, C3, C4) per kW of nominal power |
|----------------------------------------------------------------------------|------------------------------------------------------------|
| Central heat generation system with boiler for biomass and ceiling heating | 29,51                                                      |
| Central heat generation system with external heat pump and floor heating   | 49,78                                                      |
| Central heat generation system with gas boiler and wall heating            | 16,73                                                      |
| Central heat generation system with heat pump and floor heating            | 49,88                                                      |

## 12.9. LCA calculator – district heating emissions projection

The following is the database used for LCA calculator emissions of district heating (in kg CO<sub>2</sub> eq./kWh of delivered energy), calculated using projections in Heat Roadmap Europe (Mathiesen, et al., 2026).

| Country               | 2025    | 2030    | 2035    | 2040    | 2045    | 2050    |
|-----------------------|---------|---------|---------|---------|---------|---------|
| <b>Austria</b>        | 0.14800 | 0.09344 | 0.06895 | 0.04446 | 0.03740 | 0.03034 |
| <b>Belgium</b>        | 0.15924 | 0.10221 | 0.07620 | 0.05019 | 0.04721 | 0.04423 |
| <b>Bulgaria</b>       | 0.17246 | 0.14153 | 0.10607 | 0.07061 | 0.05686 | 0.04311 |
| <b>Cyprus</b>         | NA      | NA      | NA      | NA      | NA      | 0.08126 |
| <b>Czech Republic</b> | 0.18161 | 0.11800 | 0.09028 | 0.06255 | 0.05393 | 0.04530 |
| <b>Germany</b>        | 0.17442 | 0.12027 | 0.08720 | 0.05414 | 0.04485 | 0.03557 |
| <b>Denmark</b>        | 0.13921 | 0.09280 | 0.06492 | 0.03704 | 0.02864 | 0.02024 |
| <b>Estonia</b>        | 0.22607 | 0.14233 | 0.10854 | 0.07475 | 0.05840 | 0.04204 |
| <b>Greece</b>         | 0.15349 | 0.08938 | 0.07198 | 0.05458 | 0.05051 | 0.04645 |
| <b>Spain</b>          | 0.13978 | 0.09315 | 0.06659 | 0.04003 | 0.03340 | 0.02677 |
| <b>Finland</b>        | 0.15147 | 0.11605 | 0.08627 | 0.05649 | 0.04864 | 0.04078 |
| <b>France</b>         | 0.13398 | 0.09818 | 0.07371 | 0.04924 | 0.04169 | 0.03414 |
| <b>Croatia</b>        | 0.14094 | 0.09912 | 0.07360 | 0.04809 | 0.04238 | 0.03668 |
| <b>Hungary</b>        | 0.15760 | 0.10140 | 0.07781 | 0.05421 | 0.04460 | 0.03500 |
| <b>Ireland</b>        | 0.15491 | 0.10192 | 0.08864 | 0.07535 | 0.06575 | 0.05615 |
| <b>Italy</b>          | 0.15800 | 0.10841 | 0.07624 | 0.04408 | 0.03754 | 0.03100 |
| <b>Lithuania</b>      | 0.14394 | 0.10580 | 0.07046 | 0.03511 | 0.02593 | 0.01676 |
| <b>Luxembourg</b>     | 0.13524 | 0.08958 | 0.05785 | 0.02612 | 0.02004 | 0.01396 |
| <b>Latvia</b>         | 0.14406 | 0.10808 | 0.07251 | 0.03694 | 0.02754 | 0.01813 |
| <b>Malta</b>          | NA      | 0.01259 | 0.01259 | 0.01259 | 0.01209 | 0.01158 |
| <b>Netherlands</b>    | 0.17239 | 0.11289 | 0.08901 | 0.06513 | 0.05680 | 0.04847 |
| <b>Poland</b>         | 0.22390 | 0.16411 | 0.11513 | 0.06615 | 0.05391 | 0.04166 |
| <b>Portugal</b>       | NA      | NA      | NA      | 0.05640 | 0.05673 | 0.05707 |
| <b>Romania</b>        | 0.15983 | 0.12062 | 0.09423 | 0.06784 | 0.06122 | 0.05460 |
| <b>Sweden</b>         | 0.13385 | 0.10745 | 0.08051 | 0.05357 | 0.04265 | 0.03172 |
| <b>Slovenia</b>       | 0.15635 | 0.10979 | 0.07894 | 0.04809 | 0.04304 | 0.03799 |
| <b>Slovakia</b>       | 0.14244 | 0.12059 | 0.09874 | 0.07689 | 0.05504 | 0.03319 |

## 12.10. LCC calculator – gas prices

Data extracted on 07/05/2026 13:48:35 from [ESTAT]

Dataset: **Gas prices for household consumers - bi-annual data (from 2007 onwards) [nrg\_pc\_202\$defaultview]**

URL: [Open in Data Browser](#)

| GEO (Labels)           | Price  | Note                                                                                                                                                                                                                                                            | Time frequency     | Half-yearly, semesterly       |
|------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|-------------------------------|
| European Union         | 0.1228 |                                                                                                                                                                                                                                                                 | SIEC               | Natural gas                   |
| Euro area              | 0.1312 |                                                                                                                                                                                                                                                                 | Energy consumption | 20-199 GJ                     |
| Belgium                | 0.0898 |                                                                                                                                                                                                                                                                 | Unit of measure    | Kilowatt-hour                 |
| Bulgaria               | 0.0648 |                                                                                                                                                                                                                                                                 | Taxes              | All taxes and levies included |
| Czechia                | 0.0961 |                                                                                                                                                                                                                                                                 | Currency           | Euro                          |
| Denmark                | 0.1257 |                                                                                                                                                                                                                                                                 |                    |                               |
| Germany                | 0.1223 |                                                                                                                                                                                                                                                                 |                    |                               |
| Estonia                | 0.0760 |                                                                                                                                                                                                                                                                 |                    |                               |
| Ireland                | 0.1300 |                                                                                                                                                                                                                                                                 |                    |                               |
| Greece                 | 0.0918 |                                                                                                                                                                                                                                                                 |                    |                               |
| Spain                  | 0.0955 |                                                                                                                                                                                                                                                                 |                    |                               |
| France                 | 0.1436 |                                                                                                                                                                                                                                                                 |                    |                               |
| Croatia                | 0.0543 |                                                                                                                                                                                                                                                                 |                    |                               |
| Italy                  | 0.1481 |                                                                                                                                                                                                                                                                 |                    |                               |
| Latvia                 | 0.0826 |                                                                                                                                                                                                                                                                 |                    |                               |
| Lithuania              | 0.0684 |                                                                                                                                                                                                                                                                 |                    |                               |
| Luxembourg             | 0.0891 |                                                                                                                                                                                                                                                                 |                    |                               |
| Hungary                | 0.0335 |                                                                                                                                                                                                                                                                 |                    |                               |
| Netherlands            | 0.1719 |                                                                                                                                                                                                                                                                 |                    |                               |
| Austria                | 0.1221 |                                                                                                                                                                                                                                                                 |                    |                               |
| Poland                 | :      |                                                                                                                                                                                                                                                                 |                    |                               |
| Portugal               | 0.1405 |                                                                                                                                                                                                                                                                 |                    |                               |
| Romania                | 0.0566 |                                                                                                                                                                                                                                                                 |                    |                               |
| Slovenia               | 0.0871 |                                                                                                                                                                                                                                                                 |                    |                               |
| Slovakia               | 0.0608 |                                                                                                                                                                                                                                                                 |                    |                               |
| Sweden                 | 0.2092 |                                                                                                                                                                                                                                                                 |                    |                               |
| Liechtenstein          | 0.1290 |                                                                                                                                                                                                                                                                 |                    |                               |
| United Kingdom         | 0.0858 | <a href="https://www.ofgem.gov.uk/information-consumers/energy-advice-households/energy-price-cap-unit-rates-and-standing-charges">https://www.ofgem.gov.uk/information-consumers/energy-advice-households/energy-price-cap-unit-rates-and-standing-charges</a> |                    |                               |
| Bosnia and Herzegovina | 0.0502 |                                                                                                                                                                                                                                                                 |                    |                               |
| Moldova                | 0.0947 |                                                                                                                                                                                                                                                                 |                    |                               |
| North Macedonia        | 0.1155 |                                                                                                                                                                                                                                                                 |                    |                               |
| Georgia                | 0.0161 |                                                                                                                                                                                                                                                                 |                    |                               |
| Albania                | :      |                                                                                                                                                                                                                                                                 |                    |                               |
| Serbia                 | :      |                                                                                                                                                                                                                                                                 |                    |                               |
| Türkiye                | 0.0232 |                                                                                                                                                                                                                                                                 |                    |                               |
| Ukraine                | :      |                                                                                                                                                                                                                                                                 |                    |                               |

Data extracted on 07/05/2026 13:50:56 from [ESTAT]

Dataset: **Gas prices for non-household consumers - bi-annual data (from 2007 onwards)**  
[nrg\_pc\_203\$defaultview]URL: [Open in Data Browser](#)

| GEO (Labels)           | Price         | Note                                                                                                                                                                                                                                                            | Time frequency     | Half-yearly, semesterly       |
|------------------------|---------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|-------------------------------|
| European Union         | 0.0720        |                                                                                                                                                                                                                                                                 | SIEC               | Natural gas                   |
| Euro area              | 0.0720        |                                                                                                                                                                                                                                                                 | Energy consumption | 10000-99999 GJ                |
| Belgium                | 0.0582        |                                                                                                                                                                                                                                                                 | Unit of measure    | Kilowatt-hour                 |
| Bulgaria               | 0.0497        |                                                                                                                                                                                                                                                                 | Taxes              | All taxes and levies included |
| Czechia                | 0.0687        |                                                                                                                                                                                                                                                                 | Currency           | Euro                          |
| Denmark                | 0.0987        |                                                                                                                                                                                                                                                                 |                    |                               |
| Germany                | 0.0857        |                                                                                                                                                                                                                                                                 |                    |                               |
| Estonia                | 0.0703        |                                                                                                                                                                                                                                                                 |                    |                               |
| Ireland                | 0.0710        |                                                                                                                                                                                                                                                                 |                    |                               |
| Greece                 | 0.0449        |                                                                                                                                                                                                                                                                 |                    |                               |
| Spain                  | 0.0615        |                                                                                                                                                                                                                                                                 |                    |                               |
| France                 | 0.0737        |                                                                                                                                                                                                                                                                 |                    |                               |
| Croatia                | 0.0510        |                                                                                                                                                                                                                                                                 |                    |                               |
| Italy                  | 0.0566        |                                                                                                                                                                                                                                                                 |                    |                               |
| Latvia                 | 0.0639        |                                                                                                                                                                                                                                                                 |                    |                               |
| Lithuania              | 0.0614        |                                                                                                                                                                                                                                                                 |                    |                               |
| Luxembourg             | 0.0709        |                                                                                                                                                                                                                                                                 |                    |                               |
| Hungary                | 0.0658        |                                                                                                                                                                                                                                                                 |                    |                               |
| Netherlands            | 0.0816        |                                                                                                                                                                                                                                                                 |                    |                               |
| Austria                | 0.0769        |                                                                                                                                                                                                                                                                 |                    |                               |
| Poland                 | 0.0796        |                                                                                                                                                                                                                                                                 |                    |                               |
| Portugal               | 0.0590        |                                                                                                                                                                                                                                                                 |                    |                               |
| Romania                | 0.0621        |                                                                                                                                                                                                                                                                 |                    |                               |
| Slovenia               | 0.0703        |                                                                                                                                                                                                                                                                 |                    |                               |
| Slovakia               | 0.0787        |                                                                                                                                                                                                                                                                 |                    |                               |
| Sweden                 | 0.1083        |                                                                                                                                                                                                                                                                 |                    |                               |
| Liechtenstein          | 0.1331        |                                                                                                                                                                                                                                                                 |                    |                               |
| United Kingdom         | 0.1006        | <a href="https://www.ofgem.gov.uk/information-consumers/energy-advice-households/energy-price-cap-unit-rates-and-standing-charges">https://www.ofgem.gov.uk/information-consumers/energy-advice-households/energy-price-cap-unit-rates-and-standing-charges</a> |                    |                               |
| Bosnia and Herzegovina | <b>0.0858</b> |                                                                                                                                                                                                                                                                 |                    |                               |
| Moldova                | 0.0622        |                                                                                                                                                                                                                                                                 |                    |                               |
| North Macedonia        | 0.0693        |                                                                                                                                                                                                                                                                 |                    |                               |
| Georgia                | 0.0543        |                                                                                                                                                                                                                                                                 |                    |                               |
| Albania                | 0.0310        |                                                                                                                                                                                                                                                                 |                    |                               |
| Serbia                 | :             |                                                                                                                                                                                                                                                                 |                    |                               |
| Türkiye                | :             |                                                                                                                                                                                                                                                                 |                    |                               |
| Ukraine                | 0.0362        |                                                                                                                                                                                                                                                                 |                    |                               |

## 12.11. LCC calculator – electricity prices

Data extracted on 07/05/2026 13:37:14 from [ESTAT]

Dataset: **Electricity prices for household consumers - bi-annual data (from 2007 onwards)**  
[nrg\_pc\_204\$defaultview]

URL: [Open in Data Browser](#)

| GEO (Labels)           | Price         | Note                                               | Time frequency     | Half-yearly, semesterly       |
|------------------------|---------------|----------------------------------------------------|--------------------|-------------------------------|
| European Union         | 0.2896        |                                                    | SIEC               | Electricity                   |
| Euro area              | 0.2999        |                                                    | Energy consumption | 2 500 - 4 999 kWh             |
| Belgium                | 0.3499        |                                                    | Unit of measure    | Kilowatt-hour                 |
| Bulgaria               | 0.1355        |                                                    | Taxes              | All taxes and levies included |
| Czechia                | 0.3217        |                                                    | Currency           | Euro                          |
| Denmark                | 0.3312        |                                                    |                    |                               |
| Germany                | 0.3869        |                                                    |                    |                               |
| Estonia                | 0.2303        |                                                    |                    |                               |
| Ireland                | 0.4042        |                                                    |                    |                               |
| Greece                 | 0.2378        |                                                    |                    |                               |
| Spain                  | 0.2669        |                                                    |                    |                               |
| France                 | 0.2561        |                                                    |                    |                               |
| Croatia                | 0.1658        |                                                    |                    |                               |
| Italy                  | 0.2966        |                                                    |                    |                               |
| Cyprus                 | 0.2774        |                                                    |                    |                               |
| Latvia                 | 0.2452        |                                                    |                    |                               |
| Lithuania              | 0.1955        |                                                    |                    |                               |
| Luxembourg             | 0.2665        |                                                    |                    |                               |
| Hungary                | 0.1082        |                                                    |                    |                               |
| Malta                  | 0.1282        |                                                    |                    |                               |
| Netherlands            | 0.2558        |                                                    |                    |                               |
| Austria                | 0.3272        |                                                    |                    |                               |
| Poland                 | 0.2709        |                                                    |                    |                               |
| Portugal               | 0.2434        |                                                    |                    |                               |
| Romania                | 0.2893        |                                                    |                    |                               |
| Slovenia               | 0.2121        |                                                    |                    |                               |
| Slovakia               | 0.1853        |                                                    |                    |                               |
| Finland                | 0.2254        |                                                    |                    |                               |
| Sweden                 | 0.2711        |                                                    |                    |                               |
| Iceland                | :             |                                                    |                    |                               |
| Liechtenstein          | 0.3062        |                                                    |                    |                               |
| Norway                 | 0.1922        |                                                    |                    |                               |
| United Kingdom         | <b>0.2886</b> | <a href="#">Sourced from OFGEM UK on 6.7.2026.</a> |                    |                               |
| Bosnia and Herzegovina | 0.0966        |                                                    |                    |                               |
| Montenegro             | 0.0998        |                                                    |                    |                               |
| Moldova                | 0.1967        |                                                    |                    |                               |
| North Macedonia        | 0.1161        |                                                    |                    |                               |
| Georgia                | 0.0731        |                                                    |                    |                               |
| Albania                | :             |                                                    |                    |                               |
| Serbia                 | 0.1190        |                                                    |                    |                               |
| Türkiye                | 0.0636        |                                                    |                    |                               |
| Ukraine                | :             |                                                    |                    |                               |
| Kosovo*                | 0.0877        |                                                    |                    |                               |

Data extracted on 07/05/2026 13:40:05 from [ESTAT]

Dataset: **Electricity prices for non-household consumers - bi-annual data (from 2007 onwards)**  
[nrg\_pc\_205\$defaultview]URL: [Open in Data Browser](#)

| GEO (Labels)           | Price  | Note                                               | Time frequency     | Half-yearly, semesterly       |
|------------------------|--------|----------------------------------------------------|--------------------|-------------------------------|
| European Union         | 0.2206 |                                                    | SIEC               | Electricity                   |
| Euro area              | 0.2247 |                                                    | Energy consumption | 500 - 4 999 MWh               |
| Belgium                | 0.2258 |                                                    | Unit of measure    | Kilowatt-hour                 |
| Bulgaria               | 0.1695 |                                                    | Taxes              | All taxes and levies included |
| Czechia                | 0.2208 |                                                    | Currency           | Euro                          |
| Denmark                | 0.2712 |                                                    |                    |                               |
| Germany                | 0.2722 |                                                    |                    |                               |
| Estonia                | 0.1748 |                                                    |                    |                               |
| Ireland                | 0.2771 |                                                    |                    |                               |
| Greece                 | 0.1844 |                                                    |                    |                               |
| Spain                  | 0.1589 |                                                    |                    |                               |
| France                 | 0.1815 |                                                    |                    |                               |
| Croatia                | 0.1749 |                                                    |                    |                               |
| Italy                  | 0.2544 |                                                    |                    |                               |
| Cyprus                 | 0.2868 |                                                    |                    |                               |
| Latvia                 | 0.1647 |                                                    |                    |                               |
| Lithuania              | 0.1920 |                                                    |                    |                               |
| Luxembourg             | 0.1860 |                                                    |                    |                               |
| Hungary                | 0.2665 |                                                    |                    |                               |
| Malta                  | 0.1420 |                                                    |                    |                               |
| Netherlands            | 0.2409 |                                                    |                    |                               |
| Austria                | 0.2383 |                                                    |                    |                               |
| Poland                 | 0.2355 |                                                    |                    |                               |
| Portugal               | 0.1622 |                                                    |                    |                               |
| Romania                | 0.2277 |                                                    |                    |                               |
| Slovenia               | 0.1834 |                                                    |                    |                               |
| Slovakia               | 0.2487 |                                                    |                    |                               |
| Finland                | 0.0938 |                                                    |                    |                               |
| Sweden                 | 0.1213 |                                                    |                    |                               |
| Iceland                | :      |                                                    |                    |                               |
| Liechtenstein          | 0.1934 |                                                    |                    |                               |
| Norway                 | 0.1033 |                                                    |                    |                               |
| United Kingdom         | 0.2886 | <a href="#">Sourced from OFGEM UK on 6.7.2026.</a> |                    |                               |
| Bosnia and Herzegovina | 0.1317 |                                                    |                    |                               |
| Montenegro             | 0.1053 |                                                    |                    |                               |
| Moldova                | 0.1891 |                                                    |                    |                               |
| North Macedonia        | 0.1464 |                                                    |                    |                               |
| Georgia                | 0.0980 |                                                    |                    |                               |
| Albania                | :      |                                                    |                    |                               |
| Serbia                 | 0.1815 |                                                    |                    |                               |
| Türkiye                | 0.1061 |                                                    |                    |                               |
| Ukraine                | :      |                                                    |                    |                               |
| Kosovo*                | :      |                                                    |                    |                               |

## 12.12. LCC calculator – district heating prices

| Country        | Gross price per kWh (EUR) | Source/Method                                                                                                                                                                                                                                                                                       |
|----------------|---------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Austria        | 0.119424                  | <a href="https://waermepreise.at/tarifuebersicht/#/">https://waermepreise.at/tarifuebersicht/#/</a>                                                                                                                                                                                                 |
| Belgium        | 0.0666                    | Attached to gas price (90%)                                                                                                                                                                                                                                                                         |
| Bulgaria       | 0.051525                  | Attached to gas price (90%)                                                                                                                                                                                                                                                                         |
| Cyprus         | 0                         |                                                                                                                                                                                                                                                                                                     |
| Czechia        | 0.154504138               | <a href="https://eru.gov.cz/vysledne-ceny-tepelne-energie-v-cr-2024">https://eru.gov.cz/vysledne-ceny-tepelne-energie-v-cr-2024</a>                                                                                                                                                                 |
| Germany        | 0.1709                    | <a href="https://www.waermepreise.info/">https://www.waermepreise.info/</a>                                                                                                                                                                                                                         |
| Denmark        | 0.122342498               | <a href="https://forsyningstilsynet.dk/Media/639116867481717406/Prisstatistik%20januar%202026%20-%20Rapport.pdf#page=5.00">https://forsyningstilsynet.dk/Media/639116867481717406/Prisstatistik%20januar%202026%20-%20Rapport.pdf#page=5.00</a>                                                     |
| Estonia        | 0.08529                   | <a href="https://www.konkurentsiamet.ee/elektter-gaas-soojus-ja-vesi-soojus/kooskolastatud-hinnad#kooskolastatud-sooju--2">https://www.konkurentsiamet.ee/elektter-gaas-soojus-ja-vesi-soojus/kooskolastatud-hinnad#kooskolastatud-sooju--2</a>                                                     |
| Greece         | 0.061515                  | Attached to gas price (90%)                                                                                                                                                                                                                                                                         |
| Spain          | 0.07065                   | Attached to gas price (90%)                                                                                                                                                                                                                                                                         |
| Finland        | 0.10897                   | <a href="https://energia.fi/tilastot/kaukolampotilastot/kaukolammon-hinta/">https://energia.fi/tilastot/kaukolampotilastot/kaukolammon-hinta/</a>                                                                                                                                                   |
| France         | 0.097785                  | Attached to gas price (90%)                                                                                                                                                                                                                                                                         |
| Croatia        | 0.11                      | <a href="https://www.hep.hr/toplinarstvo/krajnji-kupci/cijene-30/30">https://www.hep.hr/toplinarstvo/krajnji-kupci/cijene-30/30</a>                                                                                                                                                                 |
| Hungary        | 0.044685                  | Attached to gas price (90%)                                                                                                                                                                                                                                                                         |
| Ireland        | 0.09045                   | Attached to gas price (90%)                                                                                                                                                                                                                                                                         |
| Italy          | 0.092115                  | Attached to gas price (90%)                                                                                                                                                                                                                                                                         |
| Lithuania      | 0.092565                  | <a href="https://www.vert.lt/siluma/Puslapiai/silumos-kainu-statistika/silumos-kainos.aspx">https://www.vert.lt/siluma/Puslapiai/silumos-kainu-statistika/silumos-kainos.aspx</a>                                                                                                                   |
| Luxembourg     | 0.072                     | Attached to gas price (90%)                                                                                                                                                                                                                                                                         |
| Latvia         | 0.11                      | <a href="https://www.sprk.gov.lv/index%2Ephp/content/tarifi-4">https://www.sprk.gov.lv/index%2Ephp/content/tarifi-4</a>                                                                                                                                                                             |
| Malta          |                           |                                                                                                                                                                                                                                                                                                     |
| Netherlands    | 0.114075                  | Attached to gas price (90%)                                                                                                                                                                                                                                                                         |
| Poland         | 0.0926                    | <a href="https://www.ure.gov.pl/pl/cieplo/ceny-wskazniki/7904,Srednie-ceny-sprzedazy-ciepla-wytworzonego-w-nalezacych-do-przedsiębiorstw-posia.html">https://www.ure.gov.pl/pl/cieplo/ceny-wskazniki/7904,Srednie-ceny-sprzedazy-ciepla-wytworzonego-w-nalezacych-do-przedsiębiorstw-posia.html</a> |
| Portugal       | 0.089775                  | Attached to gas price (90%)                                                                                                                                                                                                                                                                         |
| Romania        | 0.06776                   | <a href="https://anre.ro/participanti-la-piata-de-energie/persoane-juridice/energie-termica/">https://anre.ro/participanti-la-piata-de-energie/persoane-juridice/energie-termica/</a>                                                                                                               |
| Sweden         | 0.098982703               | <a href="https://nilsholgersson.nu/rapporter/rapport-2025/">https://nilsholgersson.nu/rapporter/rapport-2025/</a><br><a href="https://www.agen-rs.si/gospodinjski/toplota/analiza-cen">https://www.agen-rs.si/gospodinjski/toplota/analiza-cen</a>                                                  |
| Slovenia       | 0.165811881               | <a href="#">Only public plants taken into account</a>                                                                                                                                                                                                                                               |
| Slovakia       | 0.1052                    | <a href="https://www.urso.gov.sk/annual-reports/">https://www.urso.gov.sk/annual-reports/</a>                                                                                                                                                                                                       |
| United Kingdom | 0.0771849                 | Attached to gas price (90%)                                                                                                                                                                                                                                                                         |

## 12.13. LCC calculator – construction price indices

Data extracted on 30/03/2026  
14:53:10 from [ESTAT]

Dataset:

Last updated: 25/03/2026 11:00

**Time frequency**

**Purchasing power parities indicator**

| TIME                   |              |
|------------------------|--------------|
| Labels                 | Construction |
| Belgium                | 87.4         |
| Bulgaria               | 70.0         |
| Czechia                | 73.4         |
| Denmark                | 120.0        |
| Germany                | 144.5        |
| Estonia                | 74.8         |
| Ireland                | 96.1         |
| Greece                 | 71.6         |
| Spain                  | 78.1         |
| France                 | 117.9        |
| Croatia                | 57.5         |
| Italy                  | 81.6         |
| Cyprus                 | 71.2         |
| Latvia                 | 78.6         |
| Lithuania              | 72.8         |
| Luxembourg             | 128.4        |
| Hungary                | 67.0         |
| Malta                  | 83.8         |
| Netherlands            | 119.4        |
| Austria                | 112.3        |
| Poland                 | 69.9         |
| Portugal               | 63.7         |
| Romania                | 57.7         |
| Slovenia               | 68.4         |
| Slovakia               | 72.1         |
| Finland                | 112.9        |
| Sweden                 | 127.8        |
| Iceland                | 106.0        |
| Norway                 | 112.6        |
| Switzerland            | 145.6        |
| United Kingdom         | :            |
| Bosnia and Herzegovina | 48.1         |
| Montenegro             | 51.4         |
| North Macedonia        | 54.6         |
| Albania                | 53.4         |
| Serbia                 | 53.9         |
| Türkiye                | 57.6         |
| United States          | :            |
| Japan                  | :            |

**Special value**

: not available

## 12.14. SRI calculator – active solutions database

| Nr | Solution name                                                               | Heating |      |      |      |      |      |      |      |     |     | Domestic hot water |        |        |        |       | Cooling |      |      |      |      |      |      |      |     |     | Ventilation |      |      |      |     |     | Monitoring and control |      |      |       |       |       |       |       |   |  |
|----|-----------------------------------------------------------------------------|---------|------|------|------|------|------|------|------|-----|-----|--------------------|--------|--------|--------|-------|---------|------|------|------|------|------|------|------|-----|-----|-------------|------|------|------|-----|-----|------------------------|------|------|-------|-------|-------|-------|-------|---|--|
|    |                                                                             | H-1a    | H-1b | H-1c | H-1d | H-1f | H-2a | H-2b | H-2d | H-3 | H-4 | DHW-1a             | DHW-1b | DHW-1d | DHW-2b | DHW-3 | C-1a    | C-1b | C-1c | C-1d | C-1f | C-1g | C-2a | C-2b | C-3 | C-4 | V-1a        | V-1c | V-2c | V-2d | V-3 | V-6 | MC-3                   | MC-4 | MC-9 | MC-13 | MC-25 | MC-28 | MC-29 | MC-30 |   |  |
| 3  | Central heat generation system with boiler (or biomass and ceiling heating) | -       | 2    | 1    | 3    | 0    | 1    | -    | 1    | 1   | 1   | -                  | 1      | 1      | 1      | 1     | -       | -    | -    | -    | -    | -    | -    | -    | -   | -   | 1           | 1    | 1    | 2    | 1   | 1   | 1                      | 0    | 0    | 1     | 0     | 0     | 0     | 0     | 1 |  |
| 8  | Central heat generation system with external heat pump and floor heating    | -       | 2    | 2    | 3    | 1    | -    | 2    | 1    | 2   | 1   | -                  | 1      | 1      | 1      | 1     | -       | 2    | 2    | 3    | 2    | 1    | 2    | 1    | 2   | 1   | 1           | 2    | 1    | 3    | 2   | 1   | 1                      | 0    | 0    | 1     | 0     | 0     | 0     | 0     | 1 |  |
| 12 | Central heat generation system with gas boiler and wall heating             | -       | 2    | 1    | 3    | -    | 1    | -    | 1    | 1   | 1   | -                  | 1      | 1      | 1      | 1     | -       | -    | -    | -    | -    | -    | -    | -    | -   | -   | 1           | 2    | 2    | 3    | 2   | 1   | 1                      | 0    | 0    | 1     | 0     | 0     | 0     | 0     | 0 |  |
| 16 | Central heat generation system with heat pump and floor heating             | -       | 2    | 2    | 3    | 1    | -    | 2    | 1    | 2   | 1   | -                  | 1      | 1      | 1      | 2     | -       | -    | -    | -    | -    | -    | -    | -    | -   | -   | 1           | 3    | 1    | 2    | 2   | 1   | 1                      | 0    | 0    | 2     | 0     | 0     | 0     | 0     | 1 |  |



## Tailored intervention solutions for future-proofing historic buildings

At FuturHist, we research and test energy-efficient retrofit interventions tailored to historic building typologies. We implement these solutions in real-life demonstration cases in Poland, Spain, Sweden and the UK. We focus on innovative solutions such as bio-based materials, internal insulation systems, window retrofits, HVAC, and RES integration.

Duration of the project: January 2024 – December 2027



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and Innovation

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