This is the accepted manuscript of the article that appeared in final form in **Renewable and Sustainable Energy Reviews** 135 : (2021) // Article ID 110332, which has been published in final form at https://doi.org/10.1016/j.rser.2020.110332.

Co-creation of local eco-rehabilitation strategies for energy improvement of historic urban areas

Egusquiza, A.[1*], Ginestet, S.[2], Espada, J.C.[3], Flores-Abascal, I.[4], Garcia-Gafaro, C.[4], Giraldo-Soto, C.[4], Claude, S.[2], Escadeillas, ~~S~~G.[2]

[1] TECNALIA, Basque Research and Technology Alliance (BRTA), Derio, Spain

[2] LMDC, University of Toulouse, INSA, UPS, France

[3] Joint Institute for Innovation Policy, Brussels, Belgium

[4] University of the Basque Country UPV/EHU, Bilbao, Spain

* Corresponding author: aitziber.egusquiza@tecnalia.com (+34 667178981)

Tecnalia, Parque Científico y Tecnológico de Bizkaia. Astondoa Bidea. Edificio 700, Derio 48160, Spain

ABSTRACT

Energy performance and thermal comfort in historic and traditional urban environments are important because of the social and cultural requirement to conserve these areas as living entities, but also for the environmental obligation to decrease the impact of existing buildings globally. The objective of ENERPAT approach is to address this global challenge from the local perspective, through the co-creation of efficient solutions that improve the energy performance of historic areas considering local techniques and skills, taking into account the whole life cycle of the solutions, and supporting local economy and business. The objective is to test the efficiency and suitability of eco-renovation strategies that have been co-created with local stakeholders and are based on traditional energy conservation measures, as a way to work with locally-based business models that can safeguard cultural aspects and enable economic development. Two living labs have been established in the cities of Vitoria-Gasteiz (Spain) and Cahors (France) in two representative buildings of the historic urban area of each city. The living labs operate as inclusive multi-agent discussion arenas with a long-term vision, where multi-criteria co-creation processes are implemented to select conservation-friendly solutions based on local materials including criteria such as operational energy, impact on heritage values, quality of life, socio-economic development and easy logistics. The energy behaviour of the buildings and the hygrothermal performance of the external walls have been studied using on-site and laboratory experiments, through an efficient partnership between local authorities and universities. Likewise, local-based refurbishment solutions that were designed in the co-creation processes have been thermally characterised in the laboratory, through thermal conductivity and guarded hot box tests. Finally, the energy improvement of the whole renovation strategy has been simulated showing the enhancement of the two buildings.

WORD COUNT: 7845

HIGHLIGHTS

- Energy efficiency of historic centres through eco-renovation and vernacular culture
- Energy transition based on co-creation and evolutionary development

- Urban labs to merge evidence-based knowledge with socio-economic considerations
- Architectural heritage is broadened to include traditional techniques
- Results of the co-creation process are tested with experimental and numerical work

KEYWORDS: Historic Building; Energy Efficiency; Urban Conservation; Living Lab; Urban Regeneration; Complex Adaptive System; Historic City

NOMENCLATURE

AHP	Analytical Hierarchy Process
CAS	Complex adaptive systems
CDW	Construction and demolition waste
CEREMA	Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement, France
CO_2	Carbon dioxide
DVS	Dynamic Vapour Sorption method
LCA	Life Cycle Assessment
MIP	Mercury Intrusion Porosity

1 INTRODUCTION

The global impact of the built environment is evident: it accounts for roughly 40% of energy-related carbon dioxide (CO_2) and 36% of worldwide final energy use [1], and it is responsible for one of the heaviest and most voluminous waste streams generated in the EU (approximately 25% - 30%) [2]. Sustainable urban conservation strategies have been proved to be a mechanism that can minimise this impact, since they contribute to the efficiency of use of resources, reusing materials and infrastructure, reducing waste and improving energy efficiency and comfort [3]. Since around 40% of the European existing buildings were constructed prior to 1960 [4], there is a global environmental call for reducing the energy demand of historic and traditional buildings and to do it in a sustainable and resource-efficient way. As recent studies have shown historic centres are an *"opportunity of intervention at a large scale"* due to their high rehabilitation requirements [5]. Besides, there is a sociocultural requirement to protect the living nature of historic environments since unoccupied buildings are hardly preserved [6]. And the conservation of the historic character of our cities is strongly linked with the wellbeing of the citizens [7], reinforcing the local identity and contributing to the sense of place [8].

The built heritage is not only the architectural and cultural value of the buildings, but it also embodies the people, the surrounding territory, the productive activity, and the construction culture that created it [9]. European Landscape Convention defines the landscape as "*an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors*" [10]. This concept has been directly linked to the urban energy transition as a system under the concept of "*energy landscape*" [11]. The historical urban landscape, as part of the traditional city [12], is the result of the materialisation of the evolution in the usage [13] and a product of evolutionary self-organisation processes [14] The capability of historic urban systems to change to satisfy new requirements without losing their identity, e.g. their adaptability, is what has ensured their survival [15]. Energy efficiency is a strategy to combat the abandonment of historic areas fighting fuel poverty through the improvement of comfort in an affordable way while contributing to climate change mitigation. Hence energy enhancement is a key component of this updating of historic environments to contemporary requirements since it is required to maintain them alive and conserved. Similarly to other processes acting at the urban scale, energy efficiency improvement is usually addressed as a linear and disconnected process, disregarding its functional complexity and unpredictability [16] and with limited inclusion of the citizens and key stakeholders [17]. But the improvement of the energy performance of traditional buildings not only changes the energy flow, but it also changes the information and material flow through processes that are shaped by human connections, governance mechanisms and business dynamics. These interactions reshape also the infrastructures and the built environment, conceived as the physical structure that upholds the urban system, and could lead historic urban areas to steadily evolve through more sustainable and resilient stages [11] [18]. In this context, the conservation of our built heritage can be a process of evolutionary improvement if its complexity is operationalised. But as literature shows when this complexity is acknowledged it is done hazily and without solid methodologies [19].

The cultural value of historic buildings and districts is not the only attribute that has to be considered; their pre-industrial nature and thermal performance are also part of their heritage. The presence of locally generated passive measures and local materials in heterogeneous envelopes, their energy capital in the form of embodied energy [20], and especially their hygrothermal behaviour, make local knowledge crucial when addressing the energy improvement of historic buildings [21]. Therefore, one of the challenges that urban conservation is facing resides in improving thermal characteristics of the built environment without impacting in its cultural integrity [22] [23] and in the global environment [24]. One method is to find solutions that are not only energetically efficient, but they also take into account local techniques and Life Cycle Assessment (LCA) [25] such as eco-renovation solutions [26]. Moreover, the use of innovative solutions based on local materials and techniques can activate the surrounding territory enhancing the employment of resources and materials, local competences and capacities. The improvement of the liveability of historic urban areas through energy efficiency and affordable comfort can make an important contribution to the interplay between socio-ecologic and techno-economic drivers not only at the urban level but also at territorial scale [18].

Energy transitions cannot be based only on techno-economic considerations. Local culture and the input from local communities have to be considered and introduced into the research agendas and planning processes [27]. Literature highlights the need for more inclusive research [19] encouraging the co-creation of knowledge and policy between researchers, social and policy actors [27]. The bottom-up inputs and local knowledge required for the optimization of intricately interconnected environments sometimes is only accessible "*to agents on the ground*" [28]. Inclusive and collaborative approaches, together with iterative planning, can engage key stakeholders in processes more similar to evolution than to design [29]. These agents can provide relevant inputs related to local construction techniques, skills and materials, specific climate conditions; and cultural and social values.

The living lab concept can be an answer to this demand if it is implemented as a co-creation arena and long-term thinking framework that include all the relevant stakeholders. Including non-governmental actors in the process of producing local solutions increases their acceptance and, consequently, leads to consumer awareness and reduction of the energy demand [30]. Two recent studies have shown also that a user-driven approach is required in the energy rehabilitation of historic buildings as the energy demand is significantly affected by user behaviours [31][32].

Historic environments, as complex adaptive systems (CAS), are spatially multi-scalar heterogeneous non-linear urban systems [33] with the ability to self-regulate as an answer to modifications [34]. Some of the factors identified by Ostrom (2009) that allow some degree of self-organisation in socio-ecological systems (manageable size of the system, number of involved actors, and importance of the resource for users) are already present in the historic urban environments and others can be accomplished by evidence-based co-creation strategies (expanding the knowledge of the system and increasing the autonomy in the decisions) [35]. Energy transitions are complex and long-term innovation processes [36] that require changes in policy culture [37] to allow stakeholders to experiment with new technologies and rules in a "*learning-by-doing"* approach [19]. In this context, we can consider local energy initiatives as "*focal points in energy transition"* [11] and the living labs can be designed for co-creating and real-time testing and learning about the social, governance and technological innovation of the solutions that can facilitate the systemic transition towards a low carbon economy. This mutual learning process has also a positive influence on the acceptance of new technologies by the user [38].

Therefore, the literature shows the need for energy improvement strategies in historic urban environments that acknowledge their urban complexity, include local perspective and knowledge, allow scientific, evidence-based experimentation and support policy development towards sustainable urban conservation. It can be concluded also that the livings labs, with a hybrid approach to co-creation, where pure orientation towards the development of products and services is merged with urban scalability and local knowledge can be an answer to this demand. But so far, this approach has not been fully applied and tested in the energy improvement of historic urban environments. The objective of this paper is to provide an operative approach to the urban conservation of historic urban environments through the enhancement of their energy performance based on living labs. This approach combines two mutually enriching processes: the generation of evidence-based local knowledge and the inclusion of local stakeholders in a co-creation process. The paper describes and compares the implementation of this approach in the cities of Cahors and Vitoria-Gasteiz (Spain).

2 MATERIAL AND METHODS

The ENERPAT approach (called after the project "Co-creación de soluciones territoriales ENergéticamente eficaces de Eco-Renovación del hábitat Residencial PATrimonial") aims to enhance the energy performance of historic urban environments adopting the challenge described by Marshall: "*how to 'plan' a kind of complexity that seems to have arisen 'naturally' in traditional cities, without planning*" [39]. As it has been concluded from the literature review, an answer could be to use the living lab concept in a twofold way: as the participation arena where the solutions that improve the energy efficiency are co-created by all the important stakeholders and, as a demonstration building representative of the whole historic urban environment to expand the knowledge regarding the urban landscape and to test the co-designed solutions. A detailed comparison of the ENERPAT approach and other methodologies for energy improvement of historic districts can be found in [18].

The living lab concept was originally developed in the business environment as a new method for customer inclusion and commitment. Since then it has been used in many fields including urban planning and management as a way to collaborate with residents and stakeholders to create new solutions with them and not only for them [40]. The nature of the multi-layered challenges that cities must face has brought about the evolution of the concept of co-creation so that it is applicable even in complex environments such as historic urban areas. In the field of urban development, the concept of urban labs has been present for quite some time, referring to research environments for urban design and community planning [41] [42]. Urban labs act as facilitators for generating quick solutions in the context of rapid change and transition situations considering multiple domains and players. This approach provides an appropriate way to consider historic urban areas as the previously mentioned interplay of socio-ecologic and techno-economic forces.

The multiscale nature of energy improvement in historic areas [6] makes a hybrid approach to these concepts necessary. It must incorporate the general elements and the orientation towards developing products and services of the original living labs at building (demonstration) scale while complementing them with some differentiating elements of the urban living labs oriented towards developing the transition to sustainability. Living labs have to be created for each urban area as laboratories in real conditions where the stakeholders of the local refurbishment system collaborate to co-create energy-efficient solutions. The specificities of each historic area (unique combination of climate, local material, construction techniques, legal framework, architectural value and intangible cultural heritage) require the solutions to be not selected but rather co-designed. The experimental nature of urban laboratories links research and innovation stakeholders with cities to translate the singularities of the urban landscape to evidence that can support the planning policies [43]. Some of the benefits of this approach are the strategic participation using real-life scenarios [44], the user-centred innovation [45][46], the experimental processes in the real environment [47] and the engagement of the main stakeholders [48][49]. The inclusion of local knowledge in the process makes possible also to take advantage of the care that the traditional architecture has instinctively given to the whole life cycle in using and reusing local materials [50].

The improvement of the energy efficiency of historical buildings requires a precise study of the current state of the envelope (including roof) and of the materials that will be used to improve its performance [25]. The experimental process developed in the approach aims to obtain three different outputs: i) generation of local knowledge and its application to support the process of eco-renovation; ii) generation of conservation-friendly eco-renovation products able to trigger the local economy and activate the territory; and iii) generation of public policies to facilitate the transition towards a low-carbon economy and sustainable historic urban areas. The implementation of this experimental framework implies the engagement of multiple stakeholders from the whole value chain of the rehabilitation systems. The stakeholders are structured in the following groups according to their roles and contributions:

- Research and innovation stakeholders: universities and research bodies that will support the generation of knowledge and give scientific inputs to the process.
- Facilitators of heritage refurbishment: local public entities and cultural heritage managers that will provide public support and safeguard the cultural values and legal framework.
- Local refurbishment industry: local craftsmen, suppliers of innovative solutions, agents of the value chain of the rehabilitation system, and construction industry representatives that will provide inputs regarding local techniques, skills and innovative solutions.
- End users and citizens who will give inputs regarding user requirements and priorities.

The process is structured in three phases, which are articulated by co-creation workshops and testing strategies: i) co-design of eco-renovation solutions, ii) co-implementation of solutions and iii) co-evaluation of the solutions. This paper focuses particularly on the design and implementation of the first phase in the historic cities of Cahors and Vitoria.

The first co-design stage seeks to prototype the eco-renovation solutions to be implemented, tested and monitored in real conditions in the demonstrator buildings. The approach, as it can be seen in Figure 2, conceives the living labs as mutual learning environments, where the co-design process is continuously fed by the scientific analysis provided by the research stakeholders (universities and research bodies) at different stages.

The generation of evidence starts with the selection of the demonstrator buildings, that are selected as buildings representative of the whole historic city The selection is done by the local stakeholders considering the similarity of these buildings with a significant percentage of the buildings in their historic centres regarding typology, year of construction, use, materials and construction techniques. These buildings are characterised to define their material and technical characteristics and their energy baseline as input to the co-creation process. For example, the representative building in Cahors was characterised by the following measurements: absolute density using a digital density meter; bulk density and porosity accessible to water with vacuum saturation; pore size distribution by Mercury Intrusion Porosity (MIP) using a porometer; and air permeability using mass flow. Similarly, in Vitoria-Gasteiz, to know the energy behaviour of the building before refurbishment, a set of tests was carried out and included: infrared thermography to detect the presence of thermal bridges and/or insulation faults, blower door test according to standard EN 13829 [51] to assess the airtightness of the building, and in-situ measurement of thermal resistance and thermal transmittance of the facade walls of the ground and first floor, according to standard ISO 9869 [52].

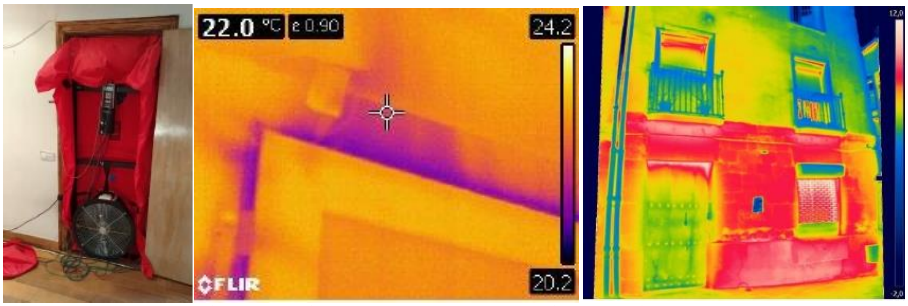


Figure 1. Blower door test (left), air infiltration through the frame of the window (centre), and infrared image of the main façade of the building (right) in the representative building of Vitoria-Gasteiz

The co-design process is structured around two workshops where the participatory and collaborative process is developed. In the first workshop, the co-creation process starts with an overview of traditional and non-traditional solutions suitable for historic buildings. An initial long list of possible options is provided to stakeholders. This list has to be shortened as recommended in the EN 16883 (Guidelines for Improving the Energy Performance of Historic Buildings) standard [53]. Repositories created by research projects focusing on energy retrofitting of traditional buildings and districts, like EFFESUS, can be used as sources [6]. A common list of criteria, and indicators that support the quantification of these criteria, is used as a mechanism to overcome one of the gaps identified in several recent energy systems research: the lack of a clear language to communicate between stakeholders with different backgrounds [19] [54]. Therefore, to reduce the long list provided by the literature on a shortlist of solutions, commonly agreed criteria are adopted as a method to support the discussion between participating agents (regarding the advantages and disadvantages, alignment with project objectives, and direct and indirect impacts of the implementation of the possible solutions). The proposed criteria include heritage impact (how much the solutions have a visual, spatial or material impact in heritage significance), environmental impact (LCA of the solutions and their potential contributions to the circular economy), operational energy (how much the solutions improve the energy efficiency), quality of life (how much the solutions improve comfort and indoor environmental quality), easy logistics (how easy are the solution to be implemented), and socio-economic development (the ability of solutions to trigger the local economy). To translate stakeholders' preferences and priorities into weighted criteria, the Analytic Hierarchy Process (AHP) method has been adopted [55]. This method converts directly the pairwise comparisons of criteria made by the stakeholders into weights for those criteria. This leads to an objective combination of the various decision-makers' assessment. The first workshops also define other requirements that the solutions must fulfil according to the stakeholders (such as supply distances, compatibility or replicability).

The long list of solutions is characterised according to the indicators and each one gets a score using the weights defined by the AHP method. In this way, a shortlist of the most promising solutions is obtained. In the second workshop, the solutions that are going to be tested in the laboratory, simulated and finally implemented in the buildings are accorded in each living lab based on the shortlist, available existing local materials and the potential impact for the local economy.

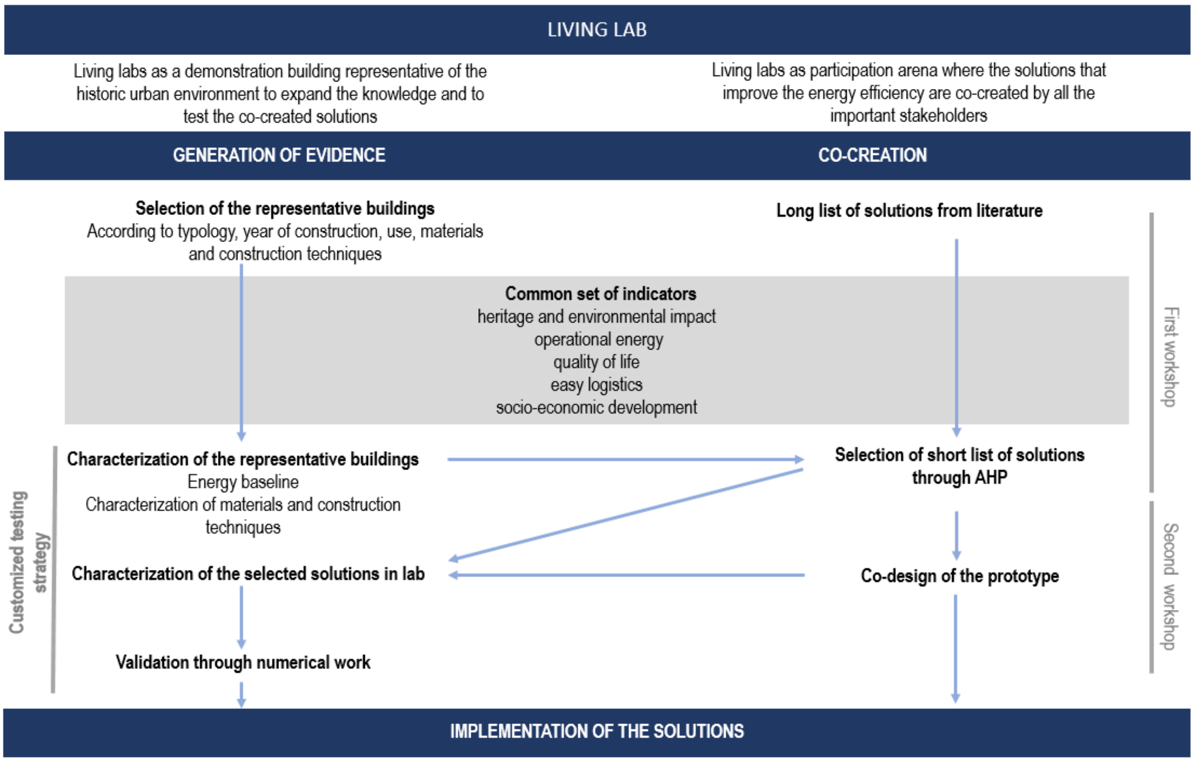


Figure 2: Workflow of the ENERPAT approach

The customized testing strategy, that will be implemented by the research and innovation stakeholders, is also decided jointly in the second workshop. Local-based eco-renovation solutions that are selected in the co-design process are thermally characterised in the laboratory, employing thermal conductivity and guarded hot box tests, to test their suitability before implementing them in the representative buildings. The test and simulations are customised by each city through collaboration with research and knowledge partners, but the common set of indicators ensures comparability of the results. As the approach is flexible, each city selects the best options to generate the required knowledge according to the building characteristics, regulatory framework, defined objectives, available resources and associated knowledge partner expertise. The final validation of the selected solution is done through numerical work. A tailored study of energy consumption and comfort level before and after renovation is conducted for the representative buildings.

3 REPRESENTATIVE BUILDINGS AS DEMONSTRATION CASES

The city centres of Cahors (a city with a population of 20 000 in southwest France) and Vitoria-Gasteiz (population 250 000 in northern Spain) face similar challenges: the physical decay of the buildings in the historic centre, the urban obsolescence and the high number of unoccupied dwellings together with socio-economic problems as fuel poverty [56]. As an answer to these problems, both cities have implemented the ENERPAT approach to select the local solutions to be applied in the demonstrator buildings. Two buildings were selected as being representative of both historic centres (Figure 3). The selection was done by the local stakeholders considering the criteria mentioned in Section 2 (typology, year of construction, use, materials and construction techniques). Additionally, it was taken into account also the rehabilitation potential (buildings with rehabilitation needs were preferred) and ownership (building with full or partial public ownerships were preferred) of the selected building to ensure the feasibility of the implementation. As input for co-design workshops, the energy performance of the buildings and the hygrothermal behaviour of the external walls were studied by on-site and laboratory experiments, through an efficient partnership between local authorities and universities. The initial state of the two buildings was very different. In Cahors, the building is part of a huge, unoccupied apartment block, made of two buildings with windows and walls in a bad state, and an uninsulated roof. The streets around are rather narrow. In contrast, the building in Vitoria is smaller and has two different solutions for its envelope. It comprises several dwellings, some of which are now occupied. These differences will determine different ways of implementing the approach and prove its flexibility.

Figure 3: Cahors (left) and Vitoria-Gasteiz (right) demonstrator buildings

4 IMPLEMENTATION

4.1 Co-design process in the cities of Cahors (France) and Vitoria-Gasteiz (Spain)

As explained in Section 2 two co-design workshops were run in each city (Figure 4). A detailed description of the living lab of Cahors at a very early stage can be found in [56]. The purposes of the first workshop were to introduce the project, approach, objectives and boundaries to the participating agents, develop the AHP exercise to identify the priorities of each city, and to present the long list of possible solutions that could fulfil the project requirements. No definitive decisions were made in this first workshop since it was crucial to leave time for personal reflection by the stakeholders and to transmit the information to their organisations before making any decision.

Figure 4: Co-creation workshops: Cahors (left) and Vitoria-Gasteiz (right)

The results of the AHP exercise were similar in both cities. The impact of the solutions on the cultural values was considered a priority in both cases as described further in the comparison of the two processes in Section 5. The only difference was that, in the case of Cahors, operational energy (optimising energy efficiency) was also considered very relevant but, in Vitoria-Gasteiz, priority was given to the quality of life (comfort and indoor environmental quality). Socio-economic development (the ability of solutions to trigger the local economy) and environmental impact (life cycle and circular economy perspective) were considered to be of medium importance in both cases, and easy logistics of low relevance. The first workshops defined also the common requirements that the solutions must fulfil. The following requirements were used later to filter the solutions:

- Existing solutions already used in the region.
- Solutions using local production, with supply distances of less than 100 km.
- Solutions that improve comfort while being compatible with: i) existing materials, ii) envelope composition, iii) hygrothermal properties of the envelope materials, and iv) chemical properties of the envelope materials.
- Solutions that improve energy efficiency, reducing the energy use in the operative phase of the building but also in the whole life cycle of the materials.
- Solutions that would be reproducible in other historic urban areas of the region.

In the second workshop, the shortlist with the solutions with the highest score (according to the weighted criteria results of the AHP exercise) were presented to the stakeholders together with the results of the research regarding the characterisation of the representative buildings as a baseline for decisions. The list was filtered by the stakeholders of the local refurbishment industry according to the common requirement defined in the first workshop. A co-design session was planned not only to select the final solutions but also to design, their configuration in the demonstrator building.

In Cahors, artisans, university and city council agents were part of the living lab and they all give their opinion to discuss which solutions were the best retrofitting practice for the walls and roof of their building. The result of the co-design process was to select old vernacular techniques, made of bio-sourced materials (such as mixes of earth and natural fibre - straw, etc.). Lime, hemp and wood fibre were selected as they are produced in proximity (less than 100 km) of Cahors.

In Vitoria-Gasteiz, it could not be determined a local material that could fulfil all the requirements. Therefore it was decided to use the demonstrator to test different solutions that after could be replicated. It was decided also to keep the masonry on the outside, so a renovation based on insulation on the inside was chosen for the ground floor. Likewise, for the first and second floor, two possible solutions were identified, both based on a renovation with thermal insulation applied on the outside: the first one based on cork panels (see description in Table 2) and the second one based on lime and hemp mortar. The pressed wood fibreboard was selected for the roof.

As explained in Section 2, the customised testing strategy is also decided in this workshop. It was decided that the experimentation in the laboratory would focus on testing different combinations of thicknesses and dosages of the selected solutions, and their thermal and hygrothermal behaviour before implementing them in the demonstrator buildings.

4.2 Experimental work

Each city decided which tests should be carried out to characterise the selected solutions in the laboratory, depending on their objectives, but the tests were mainly focused on the envelope materials. According to the different scenarios, the refurbishment of the two demonstrators had different scopes, so the tests carried out to determine the hygrothermal properties of the retrofitting materials were different for Cahors and Vitoria-Gasteiz.

4.2.1 Experimental work in Cahors

The thermal characterisation of the original bricks and stones in Cahors included: measurements of conductivity and thermal effusivity using the hot wire method, measurement of dry heat capacity using the calorimetric method, determination of the sorption isotherm by the Dynamic Vapour Sorption method (DVS), and measurement of water absorption by capillarity.

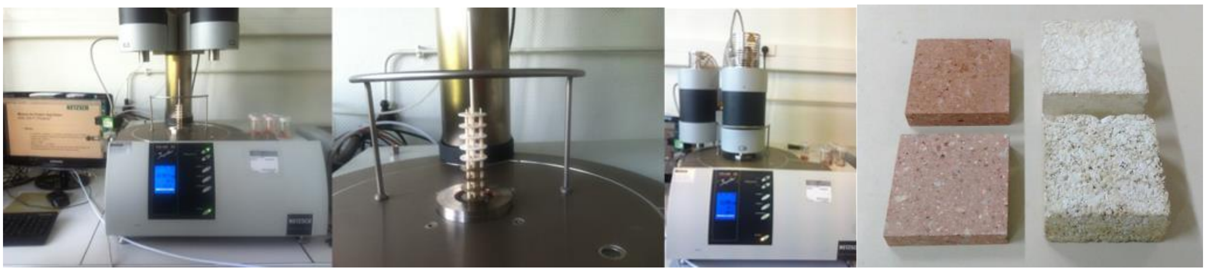


Figure 5: Measurement of the heat capacity by differential scanning calorimetry (left). 18th century brick (top left), 16th century brick (bottom left), CC1 (bottom right), CC2 (top right)

As explained in Section 4.1 the result of the co-design process was to select old vernacular techniques, made of bio-sourced materials. The physical properties of these traditional solutions (especially hygrothermal properties) were tested in the lab. Chosen solutions were then tested and enhanced in the university (mainly optimum mix ingredients and hygrothermal modelling) to be later settled in the real building in a workshop with a carpenter, an artisan, and a student (Figure 6).

Figure 6: Refurbishment of an external wall with apprentice craftsmen, source [56]

Two formulations of a lime-hemp mixture were characterised in the laboratory. The choice of formulations and samples of lime-hemp mixtures was made by a craftsman participating in the living lab. Given the difficulty of cutting the lime-hemp material, moulds the size of the desired specimens were made beforehand. The formulations studied are presented in Table 1 and are habitually used for establishment in bunch (formulation CC1) and coating (formulation CC2).

Table 1: Mass composition of the two lime-hemp mixtures studied for the demonstrator of Cahors

	CC1 (mass %)	CC2 (mass %)
Lime	33	31.5
Hemp	13	6
Sand	-	14.5
Water	54	47

The solutions were also carefully tested on-site before their application in the demo building [56].

4.2.2 Experimental work in Vitoria

As explained in Section 4.1, during the co-creation process for Vitoria a renovation based on insulation on the inside was chosen for the ground floor, and for the first and second floor two possible solutions were identified, both based on a renovation with thermal insulation applied on the outside: the first one based on cork panels and the second one based on lime and hemp mortar. For the latter, the influence of the process of application (manual or mechanical) was also studied, because it showed a big influence in the thermal conductivity of the material (related mainly to its density).

Figure 7: Cross-section of the refurbishment solution based on corkboard.

Table 2: Description of the solutions identified for the demonstrator of Vitoria-Gasteiz

Solution	Description	Comments
INS_0	4 cm of recycled cotton fibre insulation + 2 cm of natural gypsum board	Only for ground floor
LHC1	8 cm of lime and hemp coating	Manually applied, Density ≃ 1400 kg/m^3
LHC2	8 cm of lime and hemp coating	Mechanically applied, Density ≃ 800 kg/m^3
ETICS	External Thermal Insulation Composite System 2.5 cm of lime-based levelling mortar + 8 cm of corkboard + lime-based finishing coat (less than 1 cm), reinforced with fibreglass mesh	

Thermal conductivity measurements were carried out using the heat flow meter method (EN 12667:2001 [57]) and the thermal resistance of the materials applied to a base wall was determined using guarded hot box tests (EN ISO 8990:1994 [58]) (see Figure 8).

Figure 8: Sample and measurement equipment for thermal conductivity (top and medium left) and wall thermal resistance (top and medium right)

Complementary tests were also carried out, such as measuring the in situ thermal resistance of the building façade, or the resistance to water vapour diffusion of samples of lime and hemp mortar (Figure 9).

Figure 9: Thermal resistance measurement in situ (left) and samples for testing water vapour transmission properties (right)

Besides, the building in Vitoria-Gasteiz was monitored. The variables measured were temperature, relative humidity, heat fluxes through the envelope, and energy consumption to maintain conditions of comfort. To accurately measure energy consumption, electric heaters were used in empty dwellings. Additionally, CO2 sensors were installed in the occupied dwellings.

4.3 Numerical work

Simulations of historical buildings, with massive and heterogeneous walls, complex geometry and important natural airflow, are challenging [59]. Therefore, the objectives of the numerical work were adapted to the requirements of each case (occupancy and existing information mainly) using simplified indicators develop specifically for traditional buildings [60].

Previous studies [61] [62] have pointed out that the morphology of the historic urban environment changes the conditions at the outer limits of the thermal models, therefore the detailed modelling of the geometry of adjacent buildings was carried out to achieve consistent results.

4.3.1 Numerical work in Cahors

In the case of Cahors, the objective of this analysis was to study energy consumption, winter comfort, summer comfort and the risk of pathology development. The energy expenditure was due to the annual electrical consumption of convectors in kWh/m², which corresponds only to energy expenditure related to heating systems; the annual electricity consumption excluding heating systems and lighting, in kWh/m²; and annual electrical consumption of lighting in kWh/m². These three elements correspond to all electricity consumption. The summer comfort was described by the number of hours of discomfort during July and August, corresponding to the number of hours exceeding 27°C [60]. The risk of pathology development and winter comfort was described by the number of hours where the surface temperature was below 12.6°C [63].

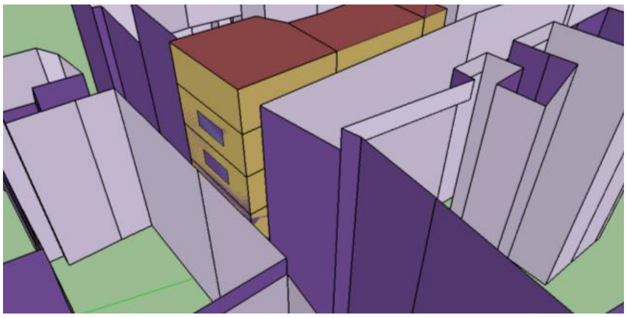


Figure 10: Demonstration building and surrounding masks - EnergyPlus

4.3.2 Numerical work in Vitoria-Gasteiz

The objective of the analysis in Vitoria-Gasteiz was to follow the evolution of the indoor temperatures of the different rooms and floors, to observe the correlation between the internal conditions, the external conditions and the intrinsic functioning of each thermal zone (power dissipation, occupation, ventilation, and shading). The temperature curve was taken to indicate the impact of these factors on the evolution of the temperature, or where the temperature peaks were found and to which phenomena they were related. Each simulated solution was analyzed to determine its impact and especially its relevance.

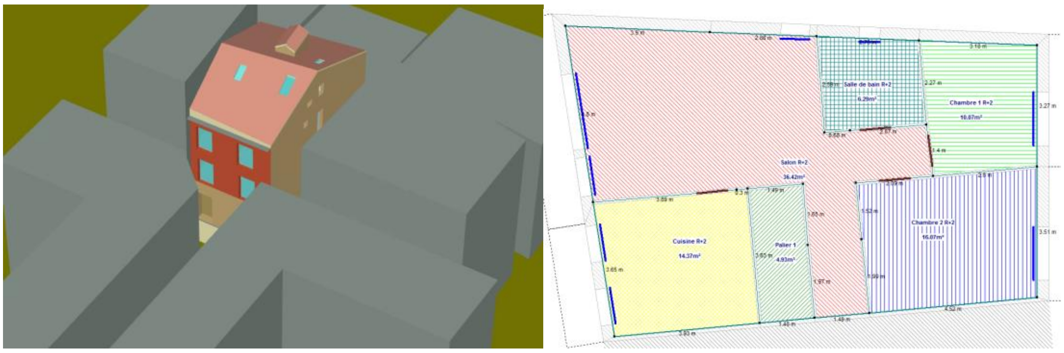


Figure 11: Demonstration building in Vitoria and surrounding masks

5 RESULTS AND DISCUSSION

5.1 Co-design process

As a result of the co-design process described in Section 3.1, the prototype demonstrator in Cahors was designed around the use of local lime and hemp for the interior and exterior envelopes of the walls and pressed wood fibre for the roof to be tested and monitored throughout the co-implementation stage. These solutions are produced in proximity (less than 100 km) and this was considered an opportunity to generate new business models based on the economy of scale engaging the agricultural sector of the region. Another advantage of these solutions was the fact that local craftsmen are used to implementing similar solutions. Unlike the situation in Cahors, in Vitoria-Gasteiz, it was not easy to identify a local material that could fulfil all the requirements since the territory had undergone profound transformations due to industrialisation. Therefore, the prototype demonstrator was conceptualised by integrating three different solutions for the interior and exterior envelope of the walls using lime hemp, lime and wood fibre, and lime and cork. Also, one solution was designed for the roof and one for the windows. The following table compares the two co-creation processes: the participants, the relevance of the different criteria and the co-designed solutions. The results of the AHP exercise were similar in both cities. The impact of the solutions on the cultural values was considered a priority in both cases as described further in the comparison of the two processes in Table 3.

Table 3: Comparison of the two processes

		CAHORS	**VITORIA-GASTEIZ**
WORKSHOPS			
Dates	**First workshop**	23/03/2017	30/03/2017
	Second workshop	6/04/2017	15/06/2017
Engaged Stakeholder	**Stakeholders facilitators of heritage refurbishment**	6 officials of Communauté d'Agglomération du Grand Cahors, refurbishment programmer	Ensanche 21 (Vitoria Municipal Council), Municipal Energy Agency (CEA)
	Local refurbishment industry	Confédération de l'artisanat et des petites entreprises du bâtiment (CAPEB)	ERAIKUNE (construction clusters of Basque Country)
	Research and innovation stakeholder	INSA laboratory (University of Toulouse), l'Association Sites & Cités Remarquables, PFT, QUERCY ENERGIE.	Santa María Cathedral Foundation, ENEDI laboratory (University of Basque Country), Tecnalia Research & Innovation.
CRITERIA/RELEVANCE			
Impact in heritage		**Very high relevance**	**Very high relevance**
Operational energy		**Very high relevance**	Medium relevance
Quality of life		High relevance	**Very high relevance**
Socio-economic development		Medium relevance	Medium relevance
Logistic easiness		Low relevance	Low relevance
Environmental impact		Medium relevance	Medium relevance
CO-DESIGNED SOLUTIONS			
Exterior envelope		Double layer on the existing masonry stone of the building, consisting of a first 7 cm wide layer made up of lime and hemp and a finishing layer of lime.	1st and 2nd floor: External Thermal Insulation System on the existing brick of the building, consisting of lime-based levelling mortar, corkboard and a finishing layer of lime.

Interior envelope	Double layer on the existing masonry stone of the building, consisting of a first, 20 cm wide layer made up of lime and hemp, and a finishing layer of lime, sand and hemp or lime and hemp.	Ground floor: A layer of recycled cotton fibre insulation and a finishing layer of natural gypsum board, put on the internal side of the existing masonry wall.
Roof	Double layer of rigid and semi-rigid wood fibre on wood board	Pressed wood fibreboard

5.2 Experimental work

5.2.1 Results of the experimental work in Cahors

The following table summarises the values measured and calculated before and after renovation in the building of Cahors. As can be seen in the table, for both walls, the addition of insulation reduced heat loss. The change is particularly noticeable for the initially very wasteful wood panel wall, where the thermal transmittance was divided by 5. For the brick wall, it was divided by 3.75. These solutions were selected for the demonstrator building.

Table 4: Measured and calculated heat transfer coefficients(U measured in-situ [$W.m^{-2}. K^{-1}$]; U calculated [$W.m^{-2}. K^{-1}$] with λ (16th century brick) = 0.49 $W.m^{-1}.K^{-1}$ and λ (18th century brick) = 0.715 $W.m^{-1}.K^{-1}$)

Material / Solution	**U value (measured in-situ)**		**U value (calculated)**	
	Before	**After**	**Before**	**After**
Brick	1.35	0.36	1.20 ± 0.07	0.43 ±0.04
			1.74 ±0.07	0.48 ±0.05
Timber frame	2.85	0.57	3.13 ± 0.09	0.55 ±0.07
			4.36 ± 0.1	0.57±0.07

5.2.2 Results of the experimental work in Vitoria-Gasteiz

In Vitoria-Gasteiz, the solutions that could be used in the demonstration building were tested in the Laboratory of Quality Control in Buildings of the Basque Government. The tests carried out provided information on the thermal behaviour of the following materials or refurbishment solutions: external coating of a mortar of lime and hemp applied manually, external coating of a mortar of lime and hemp applied by machine, wood fibreboard, and natural cork panel. As the hygroscopic properties are also important in historic buildings, in addition to the thermal tests, the resistance to the diffusion of water vapour was determined on a sample of lime and hemp. Two dwellings were tested to assess their air permeability. The air change rate values obtained at 50 Pa were 8.7 for the ground floor and 10.4 for the first floor. These values are very high so, if a ventilation system with heat recovery would be installed, concrete measures will have to be adopted to significantly reduce these values. The values obtained in the conductivity tests were:

Table 5: Conductivity values of the materials

Material / Solution	**k [W/m·K]**	**Comments**
Wood fibre board	0.045 ± 0.02	
Natural cork panel	0.059 ± 0.02	
Lime and hemp ($\rho \simeq 650$ kg/m^3)	0.13 ± 0.01	(Conditioned at 20ºC and 50% RH)
	0.12 ± 0.01	(Dried in oven at 70 ºC)

Two samples of lime and hemp coatings, with different methods of application to the wall, were tested in the laboratory. The results were quite different, mainly because of the difference in the water contents of the samples, which led to a marked density difference between the samples. The thermal resistance values obtained with the two samples are shown in the next table.

Table 6: Thermal resistance values of the tested solutions for Vitoria-Gasteiz

Material / Solution	R [m2·K/W]	Comments
8 cm of lime and hemp coating (LHC1)	0.24	Guarded hot box test. Manually applied, density ≃ 1400 kg/m^3
8 cm of lime and hemp coating (LHC2)	0.55	Guarded hot box test. Mechanically applied, density ≃ 800 kg/m^3
2.5 cm of lime based levelling mortar + 8 cm of corkboard + lime based finishing coat (ETICS)	1,65	Guarded hot box test.

Since LHC2 showed better thermal performance, its vapour diffusion resistance factor was determined by the test, to know the hygroscopic behaviour. The value obtained was $\mu = 19.3 \pm 2.8$, a value in the range of the lime-based materials.

Finally, the thermal transmittance of the two different façade solutions existing in the building was investigated in the in-situ tests. The values obtained and the improvement that would be achieved both on the ground floor (with INS_0) and in the first and second floor (with ETICS) are shown in the next table.

Table 7: Tested and predicted thermal transmittance values for Vitoria-Gasteiz

Material / Solution	U [W/m^2·K]	Comments
Masonry (Ground floor)	0.82	In situ test. Total thickness = 0.76 m.
Masonry + INS_0	0.43	Predicted value
Moulded brick wall + Fiberglass + Plaster (First floor)	0.46	In situ test. Total thickness = 0.36 m.
Moulded brick wall + Fiberglass + Plaster + ETICS solution	027	Predicted value

As mentioned above, the thermal characteristics of the tested solutions were all quite good, so other criteria, such as hygroscopic compatibility, were taken into consideration when the refurbishment solutions were selected.

5.3 Numerical work

5.3.1 Results of the numerical work of Cahors

For the thermal simulation of the demonstrator building of Cahors, the building was divided into three different dwellings: a co-working space (level 0 and 1), and two apartments to rent: a small one (for students at level 2) and a duplex flat (for a family at level 3 and 4, with a rooftop), and the energy consumption was simulated for each of them (Figure 12).

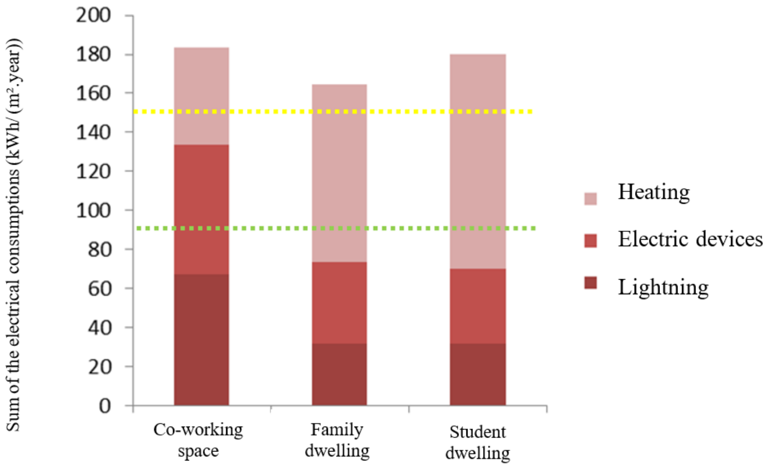


Figure 12: Energy consumption after refurbishment in Cahors

As expected, this numerical analysis nevertheless highlights a significant energy gain thanks to the different renovation systems in each of the spaces of the demonstrator building (see Table 8). For the three spaces, the simple change of windows from simple glazing to efficient double glazing reduces the electricity consumption related to heating by about ¼.

Table 8: Comparison of the energy gain (heating) according to the renovation technique and the spaces of the demonstrator building

	Energy-saving (reduction of the electrical consumption of heating)		
	Co-Working office	**Student dwelling**	**Family dwelling**
Double glazing	26.35%	23.78%	23.29%
Opaque wall insulation	44.65%	35.93%	35.88%
Attic insulation + double glazing + opaque wall insulation	71.15%	62.05%	62%

Despite the renovation, the co-working space keeps a cumulative amount of electricity consumption close to 150 kWh/m² due to the use of this space (lighting and electrical appliances). The occupancy and consumption scenarios were inspired by French thermal regulation, RT2012, and sometimes seem inappropriate, especially concerning the continuous use of lighting during hours of presence. The buildings studied have good summer comfort when not in use, i.e. without occupants, thanks to the reduction of the access of solar radiation and the inertia and strong contiguity of the buildings. No time of discomfort is noted during simulations without occupants, either before or after renovation. Calculations made with the occupant show that users play a decisive role as it has been mentioned by recent literature [31] [59]. Before the renovation, the internal loads due to electrical equipment and the occupant become too great in the upper part of the co-working space, and also in the upper north room of the family apartment (Figure 13).

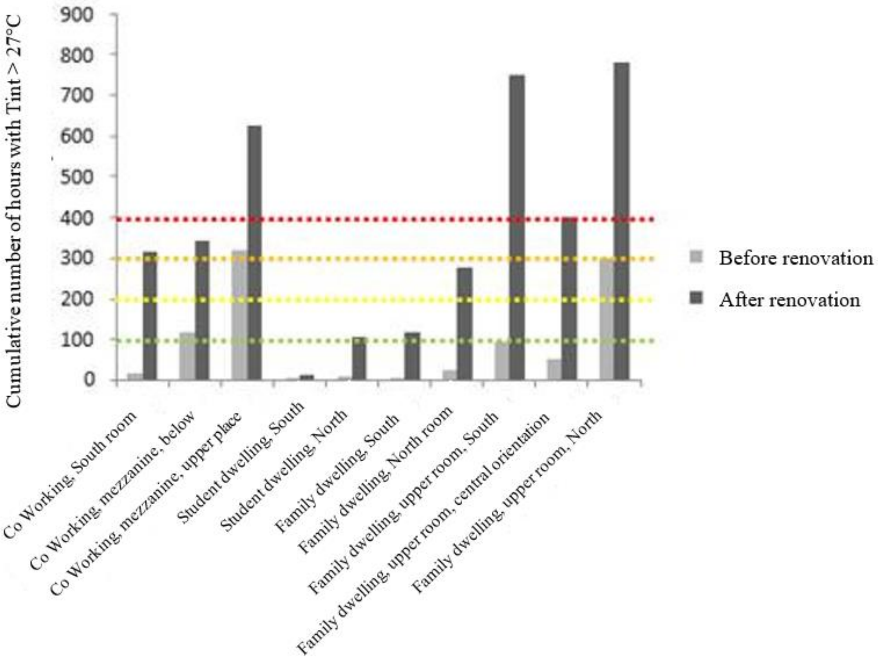


Figure 13: Number of hours of discomfort in use before and after renovation in Cahors

Thermal renovation, by accentuating the confinement, increases the number of hours of discomfort for each room. For low-volume rooms (southern part of the demonstrator building), this increase is particularly noticeable. However, in historic buildings, the limitation of existing main commercial thermal simulation softwares has to be considered, since they do not take the moisture buffering effect of walls into account, neither the effect of lime-hemp insulation in the improvement of the comfort by the regulation of the humidity of the room. The measurements carried out in situ after renovation, taken in combination with this numerical study and the study of the occupants' sensation of comfort, will make it possible to better evaluate the influence on the comfort of installing an interior, bio-based insulation.

5.3.2 Results of the numerical work of Vitoria-Gasteiz

In the case of Vitoria-Gasteiz before the renovation, the building was occupied only on the second floor and in the attic. The building envelope was not insulated, but windows in the occupied area were double-glazed from a previous renovation, the rest of the windows being single glazed. No heating system was present other than in the occupied part of the building. In this zone, the heating was managed by a gas boiler and the heat was emitted via wall heaters with hot water. The building was permanently heated to a set temperature of 21°C with a possible reduction to 19°C overnight. No mechanical ventilation was present. Except for the occupied part, no additional window opening to discharge the heat of the building and no management of mobile protections was considered. Although the unoccupied areas of the building were devoid of insulation and heating, a first study of the annual temperature curves showed that, by its structure, the building had good inertia (Figure 14).

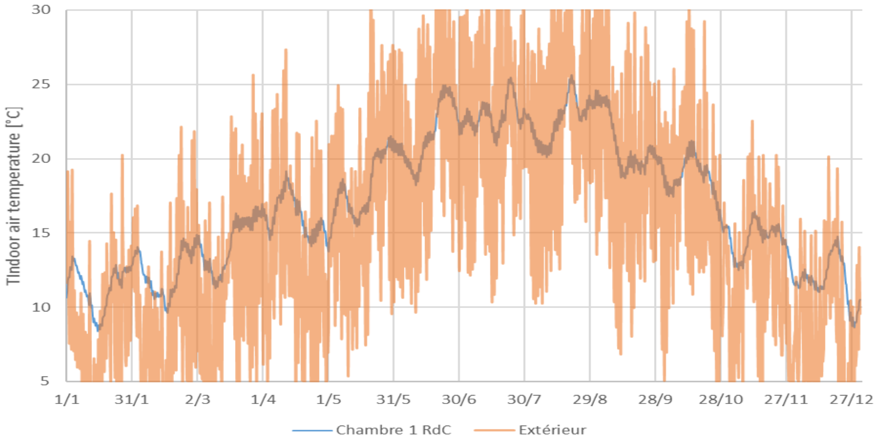


Figure 14: Inertia on the ground floor of the building in Vitoria-Gasteiz

The analysis of indoor temperature rise for increasingly high levels in the building shows stratification of air in the building, especially in the summer. In winter, it is noted that the temperatures of the second floor are lower than that of the first, which is suggestive of precarious insulation of the roof.

Table 9: The indoor temperature at several building levels in Vitoria-Gasteiz

	T° Min	**T° Mean**	**T° Max**
	[°C]	**[°C]**	**[°C]**
Kitchen second floor	10.6	19.5	32.5
Bedroom 2 second floor	9.5	18.5	28.3
Bedroom 1 first floor	12.5	18.6	25.2
Kitchen first floor	12.0	18.8	26.8
Kitchen ground floor	10.0	17.5	25.0
Bedroom 1 ground floor	8.4	17.1	25.7

For the building forecasts after renovation, the phase shift of the temperature and the limited variation of the temperature seen in the first results demonstrate that the thermal inertia of the building is always very good.

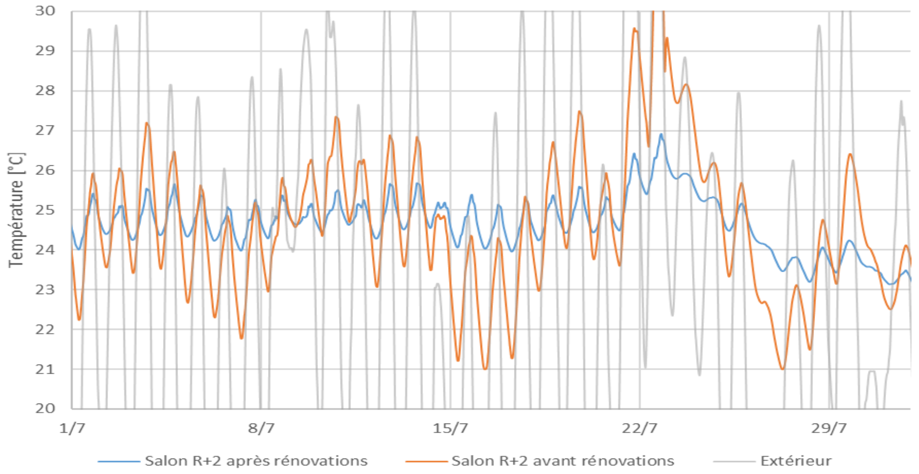


Figure 15: Comparison of temperature during July before and after renovations

Due to its more efficient envelope, the building is less sensitive to variations in the climate of Vitoria-Gasteiz. This allows it to exceed the temperature of discomfort a maximum of 5 times at most in the year, so the building can be described as comfortable.

In terms of energy consumption, if we compare what is comparable, namely the occupied part on the second floor, the energy-saving achieved is substantial. Although the implementation of controlled mechanical ventilation induces much higher electrical consumption, on an overall balance (that is to say, taking heating needs, DHW, ventilation, electrical appliances, etc. into account) the renovations will allow energy savings of more than 50%, as shown in Table 10. The efficiency of the building envelope allows almost 79% savings in heating. Once again, in-situ measurements will be carried out after this renovation, in addition to this numerical study, as a part of the co-creation process.

Table 10: Energy consumption before and after refurbishment in Vitoria-Gasteiz

	Before renovations		**After renovations**	
Zone	**Gas (PCS)**	**Electricity**	**Gas (PCS)**	**Electricity**
Heating	32 607 kWh	69 kWh	6 905 kWh	34 kWh
Domestic hot water	6 535 kWh	9 kWh	6 535 kW	-
Auxiliary ventilation units	-	-	-	2 040 kWh
Auxiliary distribution units	-	26 kWh	-	20 kWh
Power dissipated	-	2 794 kWh	-	2 794 kWh
TOTAL	**39 142 kWh**	**105 kWh**	**13 440 kWh**	**4 888 kWh**
ENERGY SAVING [Before – After]			**+25 702 kWh (+65.7%)**	**-4 783 kWh (-306.6%)**
TOTAL ENERGY SAVING			**+20 919 kWh (+53.3%)**	

6 CONCLUSIONS AND FUTURE WORK

The ENERPAT approach can be considered as a change in the way we see the energy improvement of historic urban areas and a step forward in the need to operationalise the vagueness of the concept of complexity in energy transitions. As previous research shows, the benefits obtained with this approach can support a systemic transformation of historic urban environments "*not only by improving its sustainability and liveability but also by reinforcing its local economy, preserving its cultural values and including all the stakeholders in the whole process*" [18]. This is aligned with place- based development, that suggest that development strategies should be based on mechanisms which "*build on local capabilities and promote innovative ideas through the interaction of local and general knowledge and endogenous and exogenous actors in the design and delivery of public policies* " [64].

The implementation of the approach has shown that the inclusion of more criteria than the usually considered cultural heritage and operational energy (such as LCA and socio-economic development) in the decision-making broadens the sustainability approach to include social and economic pillars. It also helps to identify traditional solutions that are locally produced so they have a smaller environmental impact and could trigger other processes beneficial for the citizens and the conservation of our cities, such the development of local economies (as the case of the hemp in Cahors).

The combination of the expertise and knowledge of the different profile of stakeholders (including heritage experts, craftsmen, end-users and knowledge partners) feeds the process providing different inputs and perspectives regarding the replicability (considering local techniques and skills), the economic and energy-saving potentials, the technical compatibility and the social acceptance of the proposed solutions. The partnership with local knowledge stakeholders (such as universities and research centres) allows the introduction of evidence-based considerations in the decision-making process and the customisation of the testing strategies fitted to the objectives, regulatory requirements and resources of each case.

The process has shown that the conservation-friendly bio-based solutions are an option that the key stakeholders identify as technically, economically, socially and culturally compatible with the historic urban landscape of their cities. The experimental and numerical work carried out showed good results also in terms of thermal behaviour in winter conditions. These solutions are recognised as efficient in the laboratory, and now the challenge is to see whether they are also efficient in real conditions, with real occupants' behaviour. Numerical simulations allow the theoretical behaviour of the buildings to be investigated in terms of comfort and energy consumption.

The flexibility of the method allows for implementation in different circumstances, as long as political long-term commitment is guaranteed to adopt an evolutionary strategy like the one described in this paper. Anyway, the cases of Cahors and Vitoria-Gasteiz show that it can be implemented gradually. Future work includes the implementation of the solutions in the representative buildings and their instrumentation to reveal the performance of these solutions in terms of summer indoor comfort, users' satisfaction, and hygrothermal behaviour. Other indicators should be also measured to monitor citizens' acceptance, fuel poverty decrease, energy reduction from an LCA perspective, and the creation of new business models at the urban level.

7 ACKNOWLEDGMENTS

This work was financially supported in the framework of the European project ENERPAT, Interreg SUDOE SOE1 / P3 / F0362 (Cocréation de solutions territoriales ENergétiquement efficaces d'Ecorénovation de l'habitat Résidentiel PATrimonial des centres anciens du

SUDOE). The authors would also like to thank to all the partners of the project for their contributions.

8 REFERENCES

[1] International Energy Agency and the United Nations Environment Programme. 2018 Global Status Report: towards a zero- emission, efficient and resilient buildings and construction sector. 2018.

[2] http://ec.europa.eu/environment/waste/construction_demolition.htm n.d.

[3] Todorović MS, Ećim-Đurić O, Nikolić S, Ristić S, Polić-Radovanović S. Historic building's holistic and sustainable deep energy refurbishment via BPS, energy efficiency and renewable energy—A case study. Energy Build 2014. https://doi.org/10.1016/j.enbuild.2014.11.011.

[4] Economidou M, Atanasiu B, Despret C, Maio J. Europe's buildings under the microscope. 2011.

[5] Gregório V, Seixas J. Energy savings potential in urban rehabilitation: A spatial-based methodology applied to historic centres. Energy Build 2017;152:11–23. https://doi.org/https://doi.org/10.1016/j.enbuild.2017.06.024.

[6] Egusquiza A, Prieto I, Izkara JL, Béjar R. Multi-scale urban data models for early-stage suitability assessment of energy conservation measures in historic urban areas. Energy Build 2018;164:87–98. https://doi.org/10.1016/j.enbuild.2017.12.061.

[7] Goldberg A, Leyden KM, Scotto TJ, Leyden KM, Goldberg A. Untangling what makes cities liveable: happiness in five cities. Proc ICE - Urban Des Plan 2012;165:127–36. https://doi.org/10.1680/udap.11.00031.

[8] Bradley D, Bradley J, Coombes M, Tranos E. Sense of Place and Social Capital and the Historic Built Environment. 2009.

[9] Egusquiza A. Multiscale information management for historic districts' energy retrofitting : a framework, a methodology, a model. Universitat Politècnica de Catalunya, 2015.

[10] Europe CO. European landscape convention. Rep. Conv., 2000.

[11] Boer J De, Zuidema C, Gugerell K. New interaction paths in the energy landscape: the role of local energy initiatives. Landsc Res 2018;43:489–502. https://doi.org/10.1080/01426397.2018.1444154.

[12] Jacobs J. The Death and Life of Great American Cities. New York: Random House; 1961.

[13] ICOMOS. The Washington Charter on the Conservation of Historic Towns and Areas 1987.

[14] Alexander C. A city is not a tree. City 1966;122:58–62.

[15] Salat S. Cities and Forms: On Sustainable Urbanism. Paris: CSTB Urban Morphology Laboratory; 2011.

[16] Winskel M, Markusson N, Jeffrey H, Candelise C, Dutton G, Howarth P, et al. Learning pathways for energy supply technologies: Bridging between innovation studies and learning rates. Technol Forecast Soc Change 2014;81:96–114. https://doi.org/10.1016/J.TECHFORE.2012.10.015.

[17] Butler C, Demski C, Parkhill K, Pidgeon N, Spence A. Public values for energy futures: Framing, indeterminacy and policy making. Energy Policy 2015;87:665–72. https://doi.org/10.1016/J.ENPOL.2015.01.035.

[18] Egusquiza A, Izkara JL, Gandini A. Energy efficiency improvement in historic urban environments : From decision support systems to co-creation strategies. 3rd Int. Conf. Energy Effic. Hist. Build., 2018, p. 576–84.

[19] Robertson Munro F, Cairney P. A systematic review of energy systems: The role of policymaking in sustainable transitions. Renew Sustain Energy Rev 2019:109598. https://doi.org/10.1016/J.RSER.2019.109598.

[20] Munarim U, Ghisi E. Environmental feasibility of heritage buildings rehabilitation. Renew Sustain Energy Rev 2016;58:235–49. https://doi.org/10.1016/j.rser.2015.12.334.

[21] Cantin R, Burgholzer J, Guarracino G, Moujalled B, Tamelikecht S, Royet BG. Field assessment of thermal behaviour of historical dwellings in France. Build Environ 2010;45:473–84. https://doi.org/10.1016/j.buildenv.2009.07.010.

[22] Martínez-Molina A, Tort-Ausina I, Cho S, Vivancos JLJL, Martinez-Molina A, Tort-Ausina I, et al. Energy efficiency and thermal comfort in historic buildings: A review. Renew Sustain Energy Rev 2016;61:70–85. https://doi.org/10.1016/j.rser.2016.03.018.

[23] Eriksson P, Hermann C, Hrabovszky-Horváth S, Rodwell D. EFFESUS Methodology for Assessing the Impacts of Energy-Related Retrofit Measures on Heritage Significance. Hist Environ Policy Pract 2014;5:132–49. https://doi.org/10.1179/1756750514Z.00000000054.

[24] Webb AL. Energy retrofits in historic and traditional buildings: A review of problems and methods. Renew Sustain Energy Rev 2017;77:748–59. https://doi.org/10.1016/J.RSER.2017.01.145.

[25] Thibodeau C, Bataille A, Sié M. Building rehabilitation life cycle assessment methodology–state of the art. Renew Sustain Energy Rev 2019;103:408–22. https://doi.org/https://doi.org/10.1016/j.rser.2018.12.037.

[26] Liu L, Li H, Lazzaretto A, Manente G, Tong C, Liu Q, et al. The development history and prospects of biomass-based insulation materials for buildings. Renew Sustain Energy Rev 2017;69:912–32. https://doi.org/https://doi.org/10.1016/j.rser.2016.11.140.

[27] Sovacool BK, Griffiths S. The cultural barriers to a low-carbon future: A review of six mobility and energy transitions across 28 countries. Renew Sustain Energy Rev 2019:109569. https://doi.org/10.1016/J.RSER.2019.109569.

[28] Colander D, Kupers R. Complexity and the art of public policy: Solving society's problems from the bottom up. 2014. https://doi.org/10.1111/gove.12292.

[29] Crawford R. What can complexity theory tell us about urban planning? 2016.

[30] Chilvers J, Foxon TJ, Galloway S, Hammond GP, Infield D, Leach M, et al. Realising transition pathways for a more electric, low-carbon energy system in the United Kingdom: Challenges, insights and opportunities. Proc Inst Mech Eng Part A J Power Energy 2017;231:440–77. https://doi.org/10.1177/0957650917695448.

[31] Berg F, Flyen A-C, Godbolt ÅL, Broström T. User-driven energy efficiency in historic buildings: A review. J Cult Herit 2017;28:188–95. https://doi.org/10.1016/J.CULHER.2017.05.009.

[32] Caro R, Sendra JJ. Evaluation of indoor environment and energy performance of dwellings in heritage buildings. The case of hot summers in historic cities in Mediterranean Europe. Sustain Cities Soc 2020;52:101798. https://doi.org/https://doi.org/10.1016/j.scs.2019.101798.

[33] Wu J. Urban ecology and sustainability: The state-of-the-science and future directions. Landsc Urban Plan 2014;125:209–21. https://doi.org/10.1016/j.landurbplan.2014.01.018.

[34] Levin S, Xepapadeas T, Crépin A-S, Norberg J, de Zeeuw A, Folke C, et al. Social-ecological systems as complex adaptive systems: Modeling and policy implications. Environ Dev Econ 2013;18:111–32. https://doi.org/10.1017/S1355770X12000460.

[35] Ostrom E. A general framework for analyzing sustainability of social-ecological systems. Science (80-) 2009. https://doi.org/10.1126/science.1172133.

[36] Geels FW. The multi-level perspective on sustainability transitions: Responses to seven criticisms. Environ Innov Soc Transitions 2011;1:24–40. https://doi.org/10.1016/J.EIST.2011.02.002.

[37] Rhodes A, Skea J, Hannon M. The Global Surge in Energy Innovation. Energies 2014;7:5601–23. https://doi.org/10.3390/en7095601.

[38] Sovacool BK, Furszyfer Del Rio DD. Smart home technologies in Europe: A critical review of concepts, benefits, risks and policies. Renew Sustain Energy Rev 2020;120:109663. https://doi.org/10.1016/J.RSER.2019.109663.

[39] Marshall S. Planning, Design and the Complexity of Cities. In: Portugali J, Meyer H, Stolk E, Tan E, editors. Complex. Theor. Cities Have Come Age, Berlin: Springer; 2012. https://doi.org/10.1007/978-3-642-24544-2_11.

[40] Bason C. Leading public sector innovationCo-creating for a better society. 2012. https://doi.org/10.1332/policypress/9781847426345.001.0001.

[41] Nevens F, Frantzeskaki N, Gorissen L, Loorbach D. Urban Transition Labs: co-creating transformative action for sustainable cities. J Clean Prod 2013;50:111–22. https://doi.org/10.1016/j.jclepro.2012.12.001.

[42] Frantzeskaki N, Wittmayer J, Loorbach D. The role of partnerships in "realising" urban sustainability in Rotterdam's City Ports Area, the Netherlands. J Clean Prod 2014. https://doi.org/10.1016/j.jclepro.2013.09.023.

[43] Evans J, Karvonen A. Give me a laboratory and I will lower your carbon footprint! Urban Laboratories and the Pursuit of Low Carbon Futures. Int J Urban Reg Res (Guest Ed 2014;38:413–30. https://doi.org/10.1111/1468-2427.1207.

[44] Reimer MH, McCormick K, Nilsson E, Arsenault N. Advancing Sustainable Urban Transformation through Living Labs: Looking to the Oresund Region. 2012.

[45] Karvonen A, Evans J, Bulkeley H, Broto VC, Hodson M, Marvin S. Living laboratories for sustainability: exploring the politics and epistemology of urban transition. Cities Low Carbon Transitions, United Kingdom: Routledge; 2011, p. 126–41.

[46] von Hippel E. Democratizing Innovation. 2005. https://doi.org/10.1111/j.1540-5885.2006.00192_2.x.

[47] Gould JD, Lewis C. Designing for usability---key principles and what designers think. Proc. SIGCHI Conf. Hum. Factors Comput. Syst. - CHI '83, 1983.

https://doi.org/10.1145/800045.801579.

[48] Chesbrough HW. The New Imperative for Creating and Profiting from Technology. 2003. https://doi.org/10.1111/j.1467-8691.2008.00502.x.

[49] Mitchell D, Coles C. The ultimate competitive advantage of continuing business model innovation 2003. https://doi.org/10.1108/02756660310504924.

[50] Rigillo M, Castagneto F, Gilchriest S. Environmental Performance of Urban Space: Rainfall Management in Sieti Village (SA). Civiltà delle acque. Passaro A., Napoli: Luciano; 2009.

[51] de Normalización y Certificación (1986- ...) AE. UNE-EN 13829:2002, aislamiento térmico, determinación de la estanquidad al aire en edificios, método de presurización por medio de ventilador. AENOR; 2002.

[52] ISO 9869-1 Thermal Insulation - Building Elements - In-situ Measurement of Thermal Resistance and Thermal Transmittance. Beuth; 2014.

[53] CEN European Commitee for Standardization. BS EN 16883 Conservation of Cultural Heritage—Guidelines for Improving the Energy Performance of Historic Buildings 2017.

[54] Nielsen AN, Jensen RL, Larsen TS, Nissen SB. Early stage decision support for sustainable building renovation – A review. Build Environ 2016;103:165–81. https://doi.org/10.1016/J.BUILDENV.2016.04.009.

[55] Saaty TL. Modeling unstructured decision problems — the theory of analytical hierarchies. Math Comput Simul 1978;20:147–58.

[56] Claude S, Ginestet S, Bonhomme M, Moulène N, Escadeillas G. The Living Lab methodology for complex environments: Insights from the thermal refurbishment of a historical district in the city of Cahors, France. Energy Res Soc Sci 2017;32:121–30. https://doi.org/10.1016/J.ERSS.2017.01.018.

[57] EN 12667: 2001 Thermal performance of building materials and products Determination of thermal resistance by means of guarded hot plate and heat flow meter methods - Products of high and medium thermal resistance. n.d.

[58] ISO 8990:1994 Thermal insulation — Determination of steady-state thermal transmission properties — Calibrated and guarded hot box n.d.

[59] Akkurt GG, Aste N, Borderon J, Buda A, Calzolari M, Chung D, et al. Dynamic thermal and hygrometric simulation of historical buildings: Critical factors and possible solutions. Renew Sustain Energy Rev 2020;118:109509. https://doi.org/https://doi.org/10.1016/j.rser.2019.109509.

[60] Héberlé E, Burgholzer J. Guidance for Finding a Sustainable Balance between Energy Efficiency, Comfort, Moisture Damage and Cultural Heritage Value in Historic Buildings. EECHB 2016 – Energy Effic. Comf. Hist. Build., Brussels: 2016, p. 52–58.

[61] Claude S. Étude expérimentale et numérique de solutions basées sur les éco-matériaux pour la rénovation thermique du patrimoine bâti urbain. 2018.

[62] Claude S, Ginestet S, Bonhomme M, Escadeillas G, Taylor J, Marincioni V, et al. Evaluating retrofit options in a historical city center: Relevance of bio-based insulation and the need to consider complex urban form in decision-making. Energy Build 2019;182:196–204. https://doi.org/10.1016/J.ENBUILD.2018.10.026.

[63] DIN 4108-2:2001-03 - Wärmeschutz und Energie-Einsparung in Gebäuden, Teil 2. Bauphysik 2001;23:178–9. https://doi.org/10.1002/bapi.200100970.

[64] Barca F, McCann P, Rodríguez-Pose A. THE CASE FOR REGIONAL DEVELOPMENT INTERVENTION: PLACE-BASED VERSUS PLACE-NEUTRAL APPROACHES*. J Reg Sci 2012;52:134–52. https://doi.org/10.1111/j.1467-9787.2011.00756.x.

9 ANNEX A – CONSTRUCTION DETAILS OF THE DEMONSTRATION BUILDINGS.

A.1 - CAHORS

Figure A.1 – General view of the building before refurbishment

Figure A.2 - View of the building during refurbishment

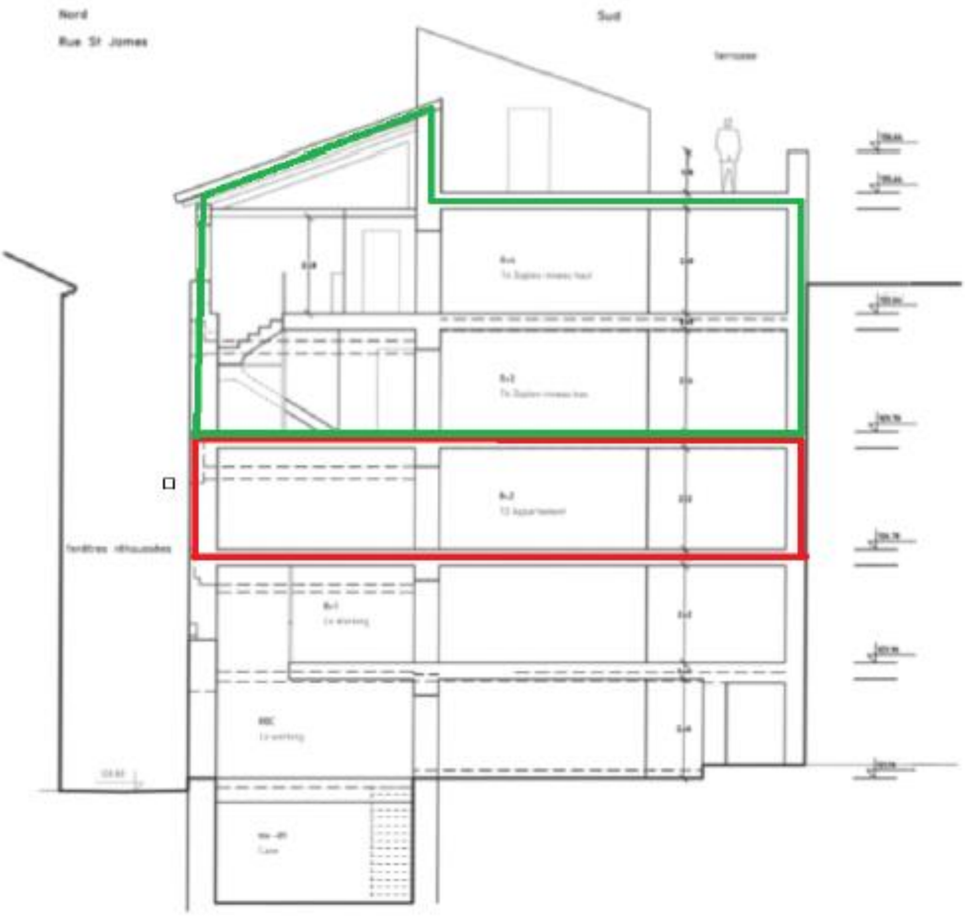


Figure A.3 - Longitudinal section of the building

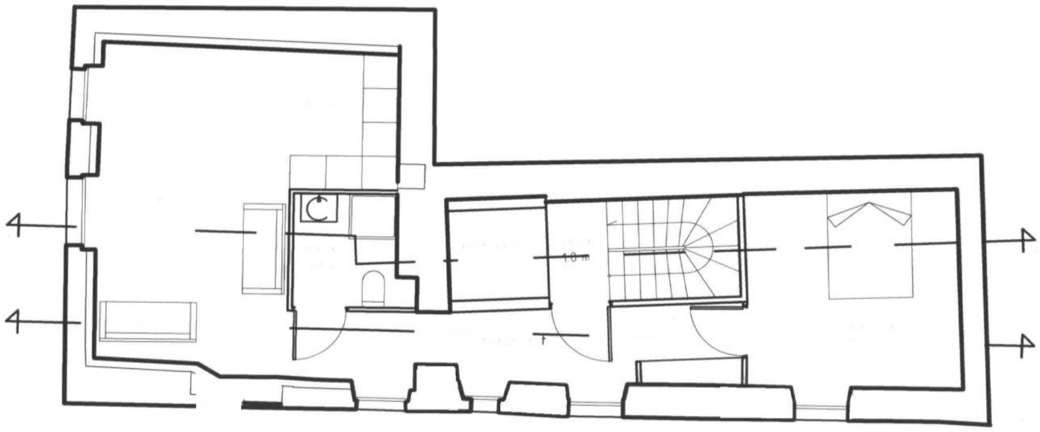


Figure A.4 - Cross-section of the building

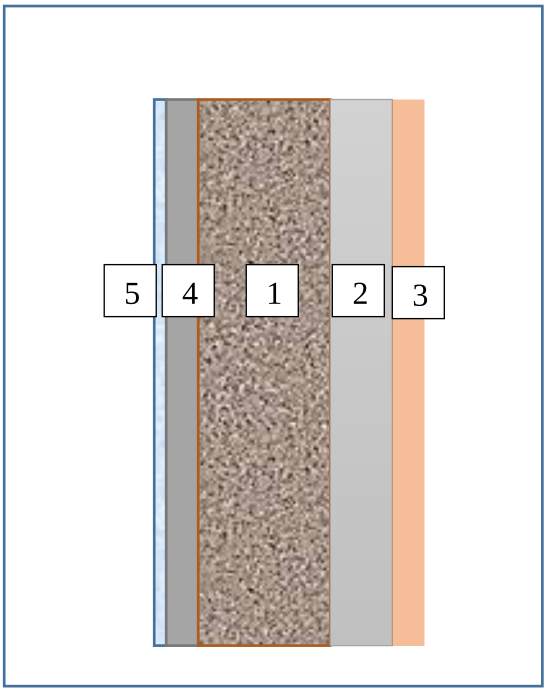


Figure A.5 – Materials used in the refurbishment of the demonstrator of Cahors

Legend: 1. Existing masonry ancient brick wall (about 40 cm), 2. Interior insulation layer: hemp concrete (20 cm), 3 Finishing layout (hearth, sand, gypsum) (about 5 cm), 4. Exterior insulation layer: hemp concrete (7 cm), 5. Outdoor finishing layout (hearth, sand, gypsum) (about 2 cm)

A.2- VITORIA-GASTEIZ

Figure A.6 - General view of the building before refurbishment

Figure A.7 - General view of the building after refurbishment

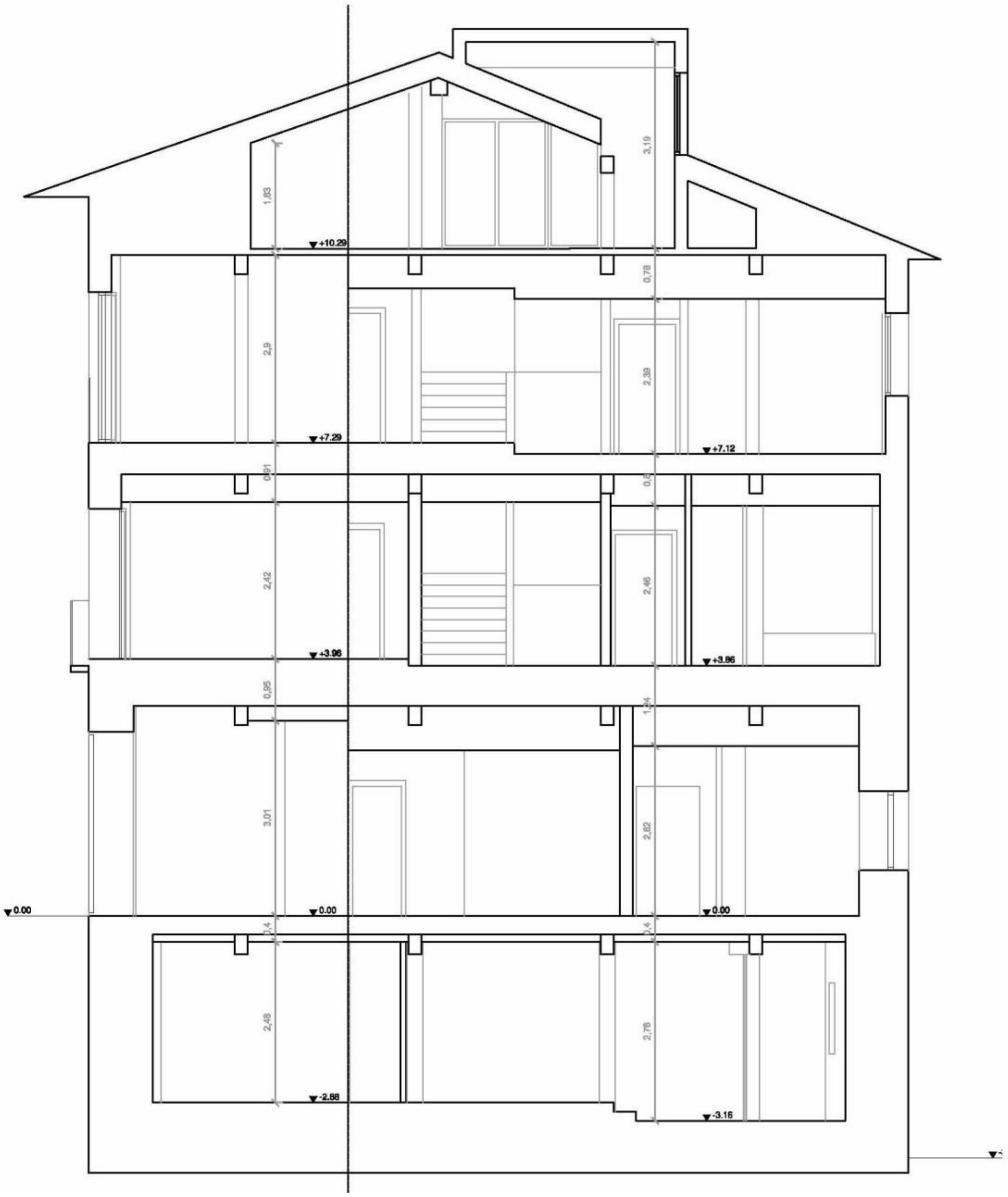


Figure A.8 - Longitudinal section of the building

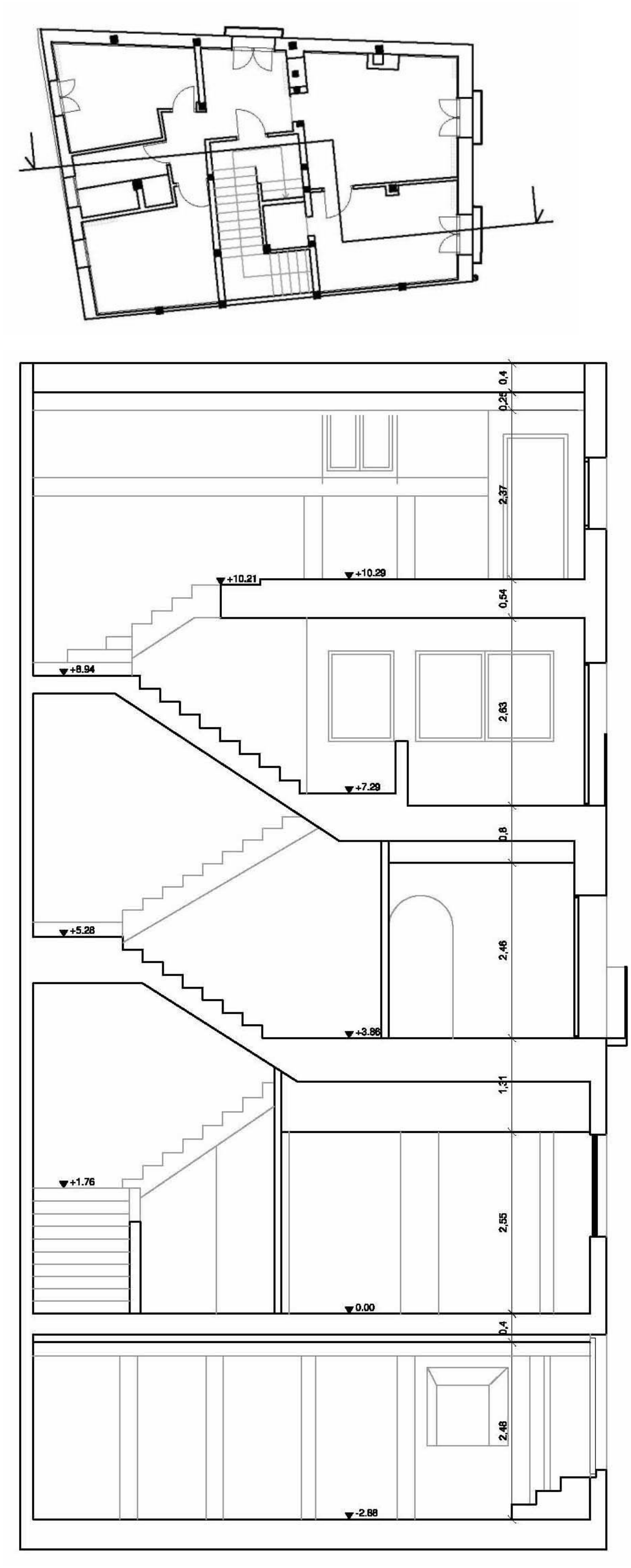
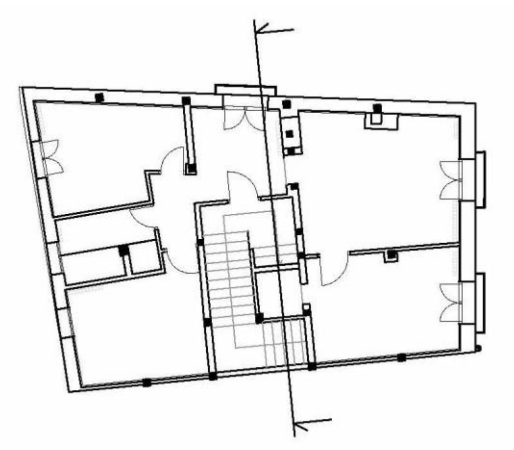
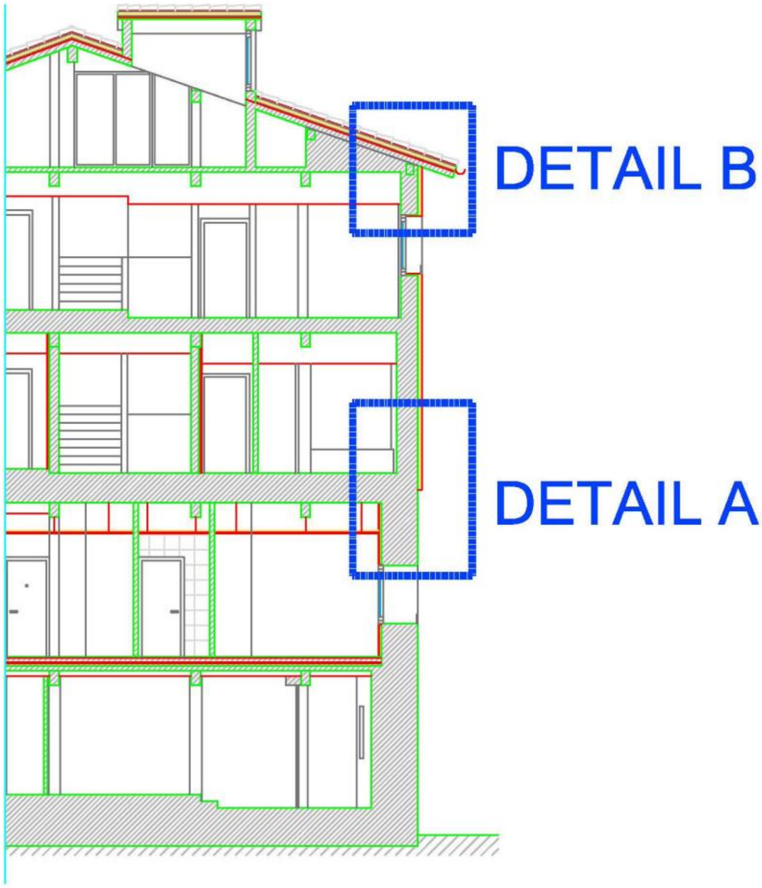
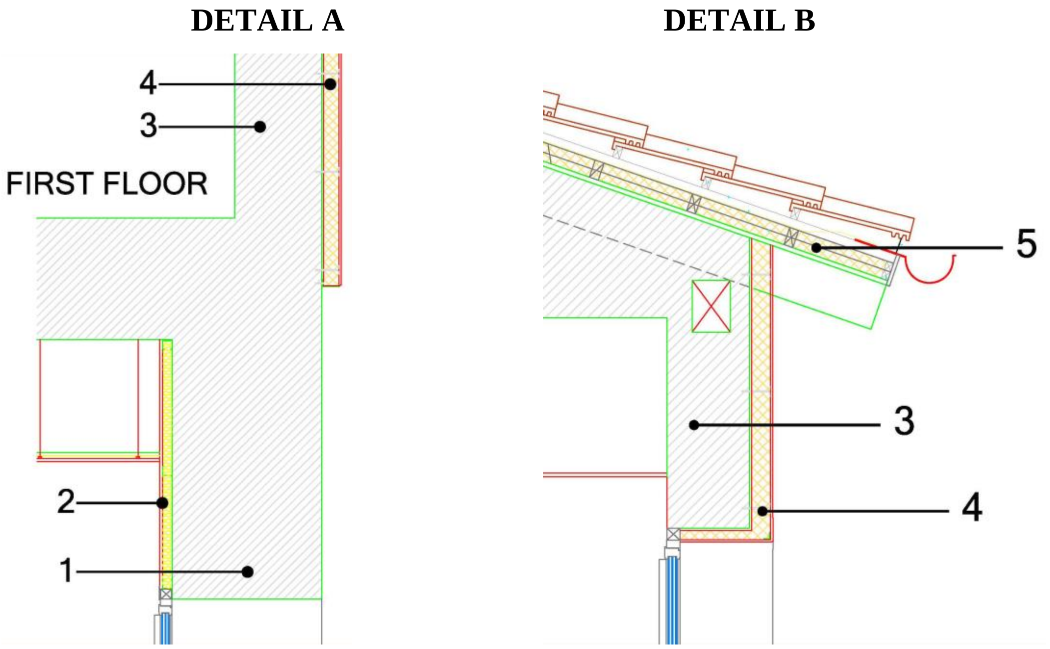


Figure A.9 - Cross-section of the building




DETAIL B
DETAIL A



DETAIL A

DETAIL B

Figure A.10 – Materials used in the refurbishment of the demonstrator of Vitoria-Gasteiz

Legend: 1. Existing masonry wall; **2.** Interior insulation layer: natural gypsum board (2 cm) and ecological Fiber Cotton panels (4 cm); **3.** Existing flattened brick wall (30 cm); **4.** ETIC Solution with cork panel (8 cm) and lime mortar; **5.** Pressed wood fibreboard under roof tiles (8 cm)

Dear Editors,

Thank you again for the opportunity to revise our manuscript, **“Co-creation of local eco-rehabilitation strategies for energy improvement of historic urban areas "** for publication in the SDEWES 2019 SI as a full-length article. We appreciate the interest that the editors and reviewers are taking in our manuscript. We have addressed the requested minor changes. We also have taken the opportunity to correct minor errors in the name of co-authors.

Thank you again for consideration of our revised manuscript.

Sincerely,

Aitziber Egusquiza, PhD

RSER AUTHOR CHECKLIST TABLE

Item	Check
Article type	• Full-length article (7861) • VSI: SDEWES 2019
Manuscript	All the details required by the Guide For Authors were included.
Cover letter	A one-page letter of introduction signed by the corresponding author has been included. All information regarding co-authors and their affiliation has been reviewed, and a previous publication is cited as the main reference for this proposal.
Layout of paper	The order of the elements/headings that make up our paper proposal is as follows: • Title • Author details • Abstract • Highlights • Keywords • Word Count • Nomenclature • 1. Introduction • 2. Material and methods • 3. Representative buildings and demonstration cases • 4. Implementation ○ 4.1. Co-design process in the cities of Cahors (France) and Vitoria-Gasteiz (Spain) ○ 4.2. Experimental work ○ 4.3. Numerical work • 5. Results and discussion ○ 5.1. Co-design process ○ 5.2. Experimental work ○ 5.3. Numerical work • 6. Conclusion and future work • 7. Acknowledgements • 8. References
English, grammar and syntax	Yes
Title	Yes
Author names and affiliations	Yes
Corresponding author	Yes. The corresponding author is clearly denoted.
Highlights	Yes
Graphical abstract	No
Copyright	Yes. The copyright aspects were checked and adhered to GFA.
Referencing style	Yes
Single column	Yes
Logos/emblems etc.	Yes
Embed graphs, tables and figures/other images in the main body of the article	Yes
Figures/Graphs/other images	Yes
Tables	Yes
Line numbering	Yes
Acknowledgements	Yes
Ethics in Publishing	Yes
Ethical Statement	Yes

Co-creation of local eco-rehabilitation strategies for energy improvement of historic urban areas

Egusquiza, A.[1*], Ginestet, S.[2], Espada, J.C.[3], Flores-Abascal, I.[4], Garcia-Gafaro, C.[4], Giraldo-Soto, C.[4], Claude, S.[2], Escadeillas, G.[2]

[1] TECNALIA, Basque Research and Technology Alliance (BRTA), Derio, Spain

[2] LMDC, University of Toulouse, INSA, UPS, France

[3] Joint Institute for Innovation Policy, Brussels, Belgium

[4] University of the Basque Country UPV/EHU, Bilbao, Spain

⁎ Corresponding author: aitziber.egusquiza@tecnalia.com (+34 667178981)

Tecnalia, Parque Científico y Tecnológico de Bizkaia. Astondoa Bidea. Edificio 700, Derio 48160, Spain

ABSTRACT

Energy performance and thermal comfort in historic and traditional urban environments are important because of the social and cultural requirement to conserve these areas as living entities, but also for the environmental obligation to decrease the impact of existing buildings globally. The objective of ENERPAT approach is to address this global challenge from the local perspective, through the co-creation of efficient solutions that improve the energy performance of historic areas considering local techniques and skills, taking into account the whole life cycle of the solutions, and supporting local economy and business. The objective is to test the efficiency and suitability of eco-renovation strategies that have been co-created with local stakeholders and are based on traditional energy conservation measures, as a way to work with locally-based business models that can safeguard cultural aspects and enable economic development. Two living labs have been established in the cities of Vitoria-Gasteiz (Spain) and Cahors (France) in two representative buildings of the historic urban area of each city. The living labs operate as inclusive multi-agent discussion arenas with a long-term vision, where multi-criteria co-creation processes are implemented to select conservation-friendly solutions based on local materials including criteria such as operational energy, impact on heritage values, quality of life, socio-economic development and easy logistics. The energy behaviour of the buildings and the hygrothermal performance of the external walls have been studied using on-site and laboratory experiments, through an efficient partnership between local authorities and universities. Likewise, local-based refurbishment solutions that were designed in the co-creation processes have been thermally characterised in the laboratory, through thermal conductivity and guarded hot box tests. Finally, the energy improvement of the whole renovation strategy has been simulated showing the enhancement of the two buildings.

WORD COUNT: 7845

HIGHLIGHTS

- Energy efficiency of historic centres through eco-renovation and vernacular culture
- Energy transition based on co-creation and evolutionary development

- Urban labs to merge evidence-based knowledge with socio-economic considerations
- Architectural heritage is broadened to include traditional techniques
- Results of the co-creation process are tested with experimental and numerical work

KEYWORDS: Historic Building; Energy Efficiency; Urban Conservation; Living Lab; Urban Regeneration; Complex Adaptive System; Historic City

NOMENCLATURE

AHP	Analytical Hierarchy Process
CAS	Complex adaptive systems
CDW	Construction and demolition waste
CEREMA	Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement, France
CO_2	Carbon dioxide
DVS	Dynamic Vapour Sorption method
LCA	Life Cycle Assessment
MIP	Mercury Intrusion Porosity

1 INTRODUCTION

The global impact of the built environment is evident: it accounts for roughly 40% of energy-related carbon dioxide (CO_2) and 36% of worldwide final energy use [1], and it is responsible for one of the heaviest and most voluminous waste streams generated in the EU (approximately 25% - 30%) [2]. Sustainable urban conservation strategies have been proved to be a mechanism that can minimise this impact, since they contribute to the efficiency of use of resources, reusing materials and infrastructure, reducing waste and improving energy efficiency and comfort [3]. Since around 40% of the European existing buildings were constructed prior to 1960 [4], there is a global environmental call for reducing the energy demand of historic and traditional buildings and to do it in a sustainable and resource-efficient way. As recent studies have shown historic centres are an *"opportunity of intervention at a large scale"* due to their high rehabilitation requirements [5]. Besides, there is a sociocultural requirement to protect the living nature of historic environments since unoccupied buildings are hardly preserved [6]. And the conservation of the historic character of our cities is strongly linked with the wellbeing of the citizens [7], reinforcing the local identity and contributing to the sense of place [8].

The built heritage is not only the architectural and cultural value of the buildings, but it also embodies the people, the surrounding territory, the productive activity, and the construction culture that created it [9]. European Landscape Convention defines the landscape as "*an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors*" [10]. This concept has been directly linked to the urban energy transition as a system under the concept of "*energy landscape*" [11]. The historical urban landscape, as part of the traditional city [12], is the result of the materialisation of the evolution in the usage [13] and a product of evolutionary self-organisation processes [14] The capability of historic urban systems to change to satisfy new requirements without losing their identity, e.g. their adaptability, is what has ensured their survival [15]. Energy efficiency is a strategy to combat the abandonment of historic areas fighting fuel poverty through the improvement of comfort in an affordable way while contributing to climate change mitigation. Hence energy enhancement is a key component of this updating of historic environments to contemporary requirements since it is required to maintain them alive and conserved. Similarly to other processes acting at the urban scale, energy efficiency improvement is usually addressed as a linear and disconnected process, disregarding its functional complexity and unpredictability [16] and with limited inclusion of the citizens and key stakeholders [17]. But the improvement of the energy performance of traditional buildings not only changes the energy flow, but it also changes the information and material flow through processes that are shaped by human connections, governance mechanisms and business dynamics. These interactions reshape also the infrastructures and the built environment, conceived as the physical structure that upholds the urban system, and could lead historic urban areas to steadily evolve through more sustainable and resilient stages [11] [18]. In this context, the conservation of our built heritage can be a process of evolutionary improvement if its complexity is operationalised. But as literature shows when this complexity is acknowledged it is done hazily and without solid methodologies [19].

The cultural value of historic buildings and districts is not the only attribute that has to be considered; their pre-industrial nature and thermal performance are also part of their heritage. The presence of locally generated passive measures and local materials in heterogeneous envelopes, their energy capital in the form of embodied energy [20], and especially their hygrothermal behaviour, make local knowledge crucial when addressing the energy improvement of historic buildings [21]. Therefore, one of the challenges that urban conservation is facing resides in improving thermal characteristics of the built environment without impacting in its cultural integrity [22] [23] and in the global environment [24]. One method is to find solutions that are not only energetically efficient, but they also take into account local techniques and Life Cycle Assessment (LCA) [25] such as eco-renovation solutions [26]. Moreover, the use of innovative solutions based on local materials and techniques can activate the surrounding territory enhancing the employment of resources and materials, local competences and capacities. The improvement of the liveability of historic urban areas through energy efficiency and affordable comfort can make an important contribution to the interplay between socio-ecologic and techno-economic drivers not only at the urban level but also at territorial scale [18].

Energy transitions cannot be based only on techno-economic considerations. Local culture and the input from local communities have to be considered and introduced into the research agendas and planning processes [27]. Literature highlights the need for more inclusive research [19] encouraging the co-creation of knowledge and policy between researchers, social and policy actors [27]. The bottom-up inputs and local knowledge required for the optimization of intricately interconnected environments sometimes is only accessible "*to agents on the ground*" [28]. Inclusive and collaborative approaches, together with iterative planning, can engage key stakeholders in processes more similar to evolution than to design [29]. These agents can provide relevant inputs related to local construction techniques, skills and materials, specific climate conditions; and cultural and social values.

The living lab concept can be an answer to this demand if it is implemented as a co-creation arena and long-term thinking framework that include all the relevant stakeholders. Including non-governmental actors in the process of producing local solutions increases their acceptance and, consequently, leads to consumer awareness and reduction of the energy demand [30]. Two recent studies have shown also that a user-driven approach is required in the energy rehabilitation of historic buildings as the energy demand is significantly affected by user behaviours [31][32].

Historic environments, as complex adaptive systems (CAS), are spatially multi-scalar heterogeneous non-linear urban systems [33] with the ability to self-regulate as an answer to modifications [34]. Some of the factors identified by Ostrom (2009) that allow some degree of self-organisation in socio-ecological systems (manageable size of the system, number of involved actors, and importance of the resource for users) are already present in the historic urban environments and others can be accomplished by evidence-based co-creation strategies (expanding the knowledge of the system and increasing the autonomy in the decisions) [35]. Energy transitions are complex and long-term innovation processes [36] that require changes in policy culture [37] to allow stakeholders to experiment with new technologies and rules in a "*learning-by-doing"* approach [19]. In this context, we can consider local energy initiatives as "*focal points in energy transition"* [11] and the living labs can be designed for co-creating and real-time testing and learning about the social, governance and technological innovation of the solutions that can facilitate the systemic transition towards a low carbon economy. This mutual learning process has also a positive influence on the acceptance of new technologies by the user [38].

Therefore, the literature shows the need for energy improvement strategies in historic urban environments that acknowledge their urban complexity, include local perspective and knowledge, allow scientific, evidence-based experimentation and support policy development towards sustainable urban conservation. It can be concluded also that the livings labs, with a hybrid approach to co-creation, where pure orientation towards the development of products and services is merged with urban scalability and local knowledge can be an answer to this demand. But so far, this approach has not been fully applied and tested in the energy improvement of historic urban environments. The objective of this paper is to provide an operative approach to the urban conservation of historic urban environments through the enhancement of their energy performance based on living labs. This approach combines two mutually enriching processes: the generation of evidence-based local knowledge and the inclusion of local stakeholders in a co-creation process. The paper describes and compares the implementation of this approach in the cities of Cahors and Vitoria-Gasteiz (Spain).

2 MATERIAL AND METHODS

The ENERPAT approach (called after the project "Co-creación de soluciones territoriales ENergéticamente eficaces de Eco-Renovación del hábitat Residencial PATrimonial") aims to enhance the energy performance of historic urban environments adopting the challenge described by Marshall: "*how to 'plan' a kind of complexity that seems to have arisen 'naturally' in traditional cities, without planning*" [39]. As it has been concluded from the literature review, an answer could be to use the living lab concept in a twofold way: as the participation arena where the solutions that improve the energy efficiency are co-created by all the important stakeholders and, as a demonstration building representative of the whole historic urban environment to expand the knowledge regarding the urban landscape and to test the co-designed solutions. A detailed comparison of the ENERPAT approach and other methodologies for energy improvement of historic districts can be found in [18].

The living lab concept was originally developed in the business environment as a new method for customer inclusion and commitment. Since then it has been used in many fields including urban planning and management as a way to collaborate with residents and stakeholders to create new solutions with them and not only for them [40]. The nature of the multi-layered challenges that cities must face has brought about the evolution of the concept of co-creation so that it is applicable even in complex environments such as historic urban areas. In the field of urban development, the concept of urban labs has been present for quite some time, referring to research environments for urban design and community planning [41] [42]. Urban labs act as facilitators for generating quick solutions in the context of rapid change and transition situations considering multiple domains and players. This approach provides an appropriate way to consider historic urban areas as the previously mentioned interplay of socio-ecologic and techno-economic forces.

The multiscale nature of energy improvement in historic areas [6] makes a hybrid approach to these concepts necessary. It must incorporate the general elements and the orientation towards developing products and services of the original living labs at building (demonstration) scale while complementing them with some differentiating elements of the urban living labs oriented towards developing the transition to sustainability. Living labs have to be created for each urban area as laboratories in real conditions where the stakeholders of the local refurbishment system collaborate to co-create energy-efficient solutions. The specificities of each historic area (unique combination of climate, local material, construction techniques, legal framework, architectural value and intangible cultural heritage) require the solutions to be not selected but rather co-designed. The experimental nature of urban laboratories links research and innovation stakeholders with cities to translate the singularities of the urban landscape to evidence that can support the planning policies [43]. Some of the benefits of this approach are the strategic participation using real-life scenarios [44], the user-centred innovation [45][46], the experimental processes in the real environment [47] and the engagement of the main stakeholders [48][49]. The inclusion of local knowledge in the process makes possible also to take advantage of the care that the traditional architecture has instinctively given to the whole life cycle in using and reusing local materials [50].

The improvement of the energy efficiency of historical buildings requires a precise study of the current state of the envelope (including roof) and of the materials that will be used to improve its performance [25]. The experimental process developed in the approach aims to obtain three different outputs: i) generation of local knowledge and its application to support the process of eco-renovation; ii) generation of conservation-friendly eco-renovation products able to trigger the local economy and activate the territory; and iii) generation of public policies to facilitate the transition towards a low-carbon economy and sustainable historic urban areas. The implementation of this experimental framework implies the engagement of multiple stakeholders from the whole value chain of the rehabilitation systems. The stakeholders are structured in the following groups according to their roles and contributions:

- Research and innovation stakeholders: universities and research bodies that will support the generation of knowledge and give scientific inputs to the process.
- Facilitators of heritage refurbishment: local public entities and cultural heritage managers that will provide public support and safeguard the cultural values and legal framework.
- Local refurbishment industry: local craftsmen, suppliers of innovative solutions, agents of the value chain of the rehabilitation system, and construction industry representatives that will provide inputs regarding local techniques, skills and innovative solutions.
- End users and citizens who will give inputs regarding user requirements and priorities.

The process is structured in three phases, which are articulated by co-creation workshops and testing strategies: i) co-design of eco-renovation solutions, ii) co-implementation of solutions and iii) co-evaluation of the solutions. This paper focuses particularly on the design and implementation of the first phase in the historic cities of Cahors and Vitoria.

The first co-design stage seeks to prototype the eco-renovation solutions to be implemented, tested and monitored in real conditions in the demonstrator buildings. The approach, as it can be seen in Figure 2, conceives the living labs as mutual learning environments, where the co-design process is continuously fed by the scientific analysis provided by the research stakeholders (universities and research bodies) at different stages.

The generation of evidence starts with the selection of the demonstrator buildings, that are selected as buildings representative of the whole historic city The selection is done by the local stakeholders considering the similarity of these buildings with a significant percentage of the buildings in their historic centres regarding typology, year of construction, use, materials and construction techniques. These buildings are characterised to define their material and technical characteristics and their energy baseline as input to the co-creation process. For example, the representative building in Cahors was characterised by the following measurements: absolute density using a digital density meter; bulk density and porosity accessible to water with vacuum saturation; pore size distribution by Mercury Intrusion Porosity (MIP) using a porometer; and air permeability using mass flow. Similarly, in Vitoria-Gasteiz, to know the energy behaviour of the building before refurbishment, a set of tests was carried out and included: infrared thermography to detect the presence of thermal bridges and/or insulation faults, blower door test according to standard EN 13829 [51] to assess the airtightness of the building, and in-situ measurement of thermal resistance and thermal transmittance of the facade walls of the ground and first floor, according to standard ISO 9869 [52].

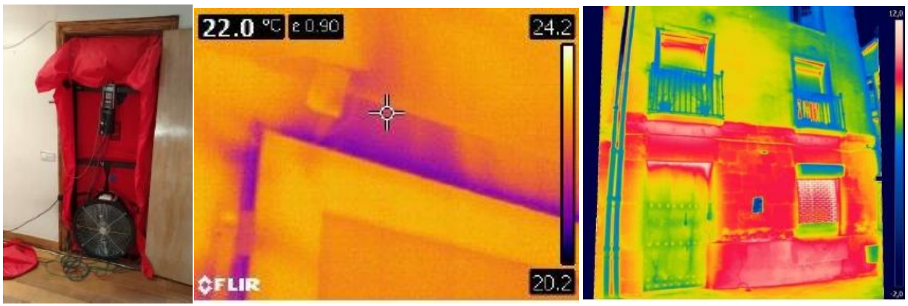


Figure 1. Blower door test (left), air infiltration through the frame of the window (centre), and infrared image of the main façade of the building (right) in the representative building of Vitoria-Gasteiz

The co-design process is structured around two workshops where the participatory and collaborative process is developed. In the first workshop, the co-creation process starts with an overview of traditional and non-traditional solutions suitable for historic buildings. An initial long list of possible options is provided to stakeholders. This list has to be shortened as recommended in the EN 16883 (Guidelines for Improving the Energy Performance of Historic Buildings) standard [53]. Repositories created by research projects focusing on energy retrofitting of traditional buildings and districts, like EFFESUS, can be used as sources [6]. A common list of criteria, and indicators that support the quantification of these criteria, is used as a mechanism to overcome one of the gaps identified in several recent energy systems research: the lack of a clear language to communicate between stakeholders with different backgrounds [19] [54]. Therefore, to reduce the long list provided by the literature on a shortlist of solutions, commonly agreed criteria are adopted as a method to support the discussion between participating agents (regarding the advantages and disadvantages, alignment with project objectives, and direct and indirect impacts of the implementation of the possible solutions). The proposed criteria include heritage impact (how much the solutions have a visual, spatial or material impact in heritage significance), environmental impact (LCA of the solutions and their potential contributions to the circular economy), operational energy (how much the solutions improve the energy efficiency), quality of life (how much the solutions improve comfort and indoor environmental quality), easy logistics (how easy are the solution to be implemented), and socio-economic development (the ability of solutions to trigger the local economy). To translate stakeholders' preferences and priorities into weighted criteria, the Analytic Hierarchy Process (AHP) method has been adopted [55]. This method converts directly the pairwise comparisons of criteria made by the stakeholders into weights for those criteria. This leads to an objective combination of the various decision-makers' assessment. The first workshops also define other requirements that the solutions must fulfil according to the stakeholders (such as supply distances, compatibility or replicability).

The long list of solutions is characterised according to the indicators and each one gets a score using the weights defined by the AHP method. In this way, a shortlist of the most promising solutions is obtained. In the second workshop, the solutions that are going to be tested in the laboratory, simulated and finally implemented in the buildings are accorded in each living lab based on the shortlist, available existing local materials and the potential impact for the local economy.

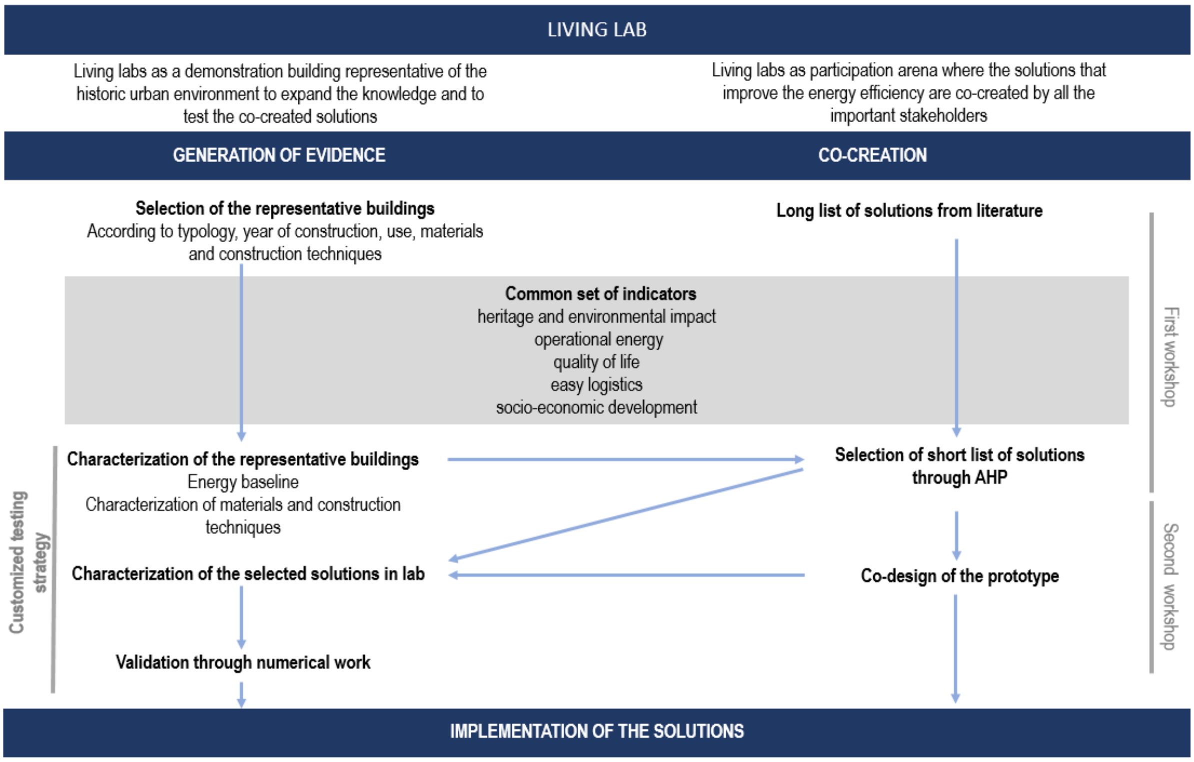


Figure 2: Workflow of the ENERPAT approach

The customized testing strategy, that will be implemented by the research and innovation stakeholders, is also decided jointly in the second workshop. Local-based eco-renovation solutions that are selected in the co-design process are thermally characterised in the laboratory, employing thermal conductivity and guarded hot box tests, to test their suitability before implementing them in the representative buildings. The test and simulations are customised by each city through collaboration with research and knowledge partners, but the common set of indicators ensures comparability of the results. As the approach is flexible, each city selects the best options to generate the required knowledge according to the building characteristics, regulatory framework, defined objectives, available resources and associated knowledge partner expertise. The final validation of the selected solution is done through numerical work. A tailored study of energy consumption and comfort level before and after renovation is conducted for the representative buildings.

3 REPRESENTATIVE BUILDINGS AS DEMONSTRATION CASES

The city centres of Cahors (a city with a population of 20 000 in southwest France) and Vitoria-Gasteiz (population 250 000 in northern Spain) face similar challenges: the physical decay of the buildings in the historic centre, the urban obsolescence and the high number of unoccupied dwellings together with socio-economic problems as fuel poverty [56]. As an answer to these problems, both cities have implemented the ENERPAT approach to select the local solutions to be applied in the demonstrator buildings. Two buildings were selected as being representative of both historic centres (Figure 3). The selection was done by the local stakeholders considering the criteria mentioned in Section 2 (typology, year of construction, use, materials and construction techniques). Additionally, it was taken into account also the rehabilitation potential (buildings with rehabilitation needs were preferred) and ownership (building with full or partial public ownerships were preferred) of the selected building to ensure the feasibility of the implementation. As input for co-design workshops, the energy performance of the buildings and the hygrothermal behaviour of the external walls were studied by on-site and laboratory experiments, through an efficient partnership between local authorities and universities. The initial state of the two buildings was very different. In Cahors, the building is part of a huge, unoccupied apartment block, made of two buildings with windows and walls in a bad state, and an uninsulated roof. The streets around are rather narrow. In contrast, the building in Vitoria is smaller and has two different solutions for its envelope. It comprises several dwellings, some of which are now occupied. These differences will determine different ways of implementing the approach and prove its flexibility.

Figure 3: Cahors (left) and Vitoria-Gasteiz (right) demonstrator buildings

4 IMPLEMENTATION

4.1 Co-design process in the cities of Cahors (France) and Vitoria-Gasteiz (Spain)

As explained in Section 2 two co-design workshops were run in each city (Figure 4). A detailed description of the living lab of Cahors at a very early stage can be found in [56]. The purposes of the first workshop were to introduce the project, approach, objectives and boundaries to the participating agents, develop the AHP exercise to identify the priorities of each city, and to present the long list of possible solutions that could fulfil the project requirements. No definitive decisions were made in this first workshop since it was crucial to leave time for personal reflection by the stakeholders and to transmit the information to their organisations before making any decision.

Figure 4: Co-creation workshops: Cahors (left) and Vitoria-Gasteiz (right)

The results of the AHP exercise were similar in both cities. The impact of the solutions on the cultural values was considered a priority in both cases as described further in the comparison of the two processes in Section 5. The only difference was that, in the case of Cahors, operational energy (optimising energy efficiency) was also considered very relevant but, in Vitoria-Gasteiz, priority was given to the quality of life (comfort and indoor environmental quality). Socio-economic development (the ability of solutions to trigger the local economy) and environmental impact (life cycle and circular economy perspective) were considered to be of medium importance in both cases, and easy logistics of low relevance. The first workshops defined also the common requirements that the solutions must fulfil. The following requirements were used later to filter the solutions:

- Existing solutions already used in the region.
- Solutions using local production, with supply distances of less than 100 km.
- Solutions that improve comfort while being compatible with: i) existing materials, ii) envelope composition, iii) hygrothermal properties of the envelope materials, and iv) chemical properties of the envelope materials.
- Solutions that improve energy efficiency, reducing the energy use in the operative phase of the building but also in the whole life cycle of the materials.
- Solutions that would be reproducible in other historic urban areas of the region.

In the second workshop, the shortlist with the solutions with the highest score (according to the weighted criteria results of the AHP exercise) were presented to the stakeholders together with the results of the research regarding the characterisation of the representative buildings as a baseline for decisions. The list was filtered by the stakeholders of the local refurbishment industry according to the common requirement defined in the first workshop. A co-design session was planned not only to select the final solutions but also to design, their configuration in the demonstrator building.

In Cahors, artisans, university and city council agents were part of the living lab and they all give their opinion to discuss which solutions were the best retrofitting practice for the walls and roof of their building. The result of the co-design process was to select old vernacular techniques, made of bio-sourced materials (such as mixes of earth and natural fibre - straw, etc.). Lime, hemp and wood fibre were selected as they are produced in proximity (less than 100 km) of Cahors.

In Vitoria-Gasteiz, it could not be determined a local material that could fulfil all the requirements. Therefore it was decided to use the demonstrator to test different solutions that after could be replicated. It was decided also to keep the masonry on the outside, so a renovation based on insulation on the inside was chosen for the ground floor. Likewise, for the first and second floor, two possible solutions were identified, both based on a renovation with thermal insulation applied on the outside: the first one based on cork panels (see description in Table 2) and the second one based on lime and hemp mortar. The pressed wood fibreboard was selected for the roof.

As explained in Section 2, the customised testing strategy is also decided in this workshop. It was decided that the experimentation in the laboratory would focus on testing different combinations of thicknesses and dosages of the selected solutions, and their thermal and hygrothermal behaviour before implementing them in the demonstrator buildings.

4.2 Experimental work

Each city decided which tests should be carried out to characterise the selected solutions in the laboratory, depending on their objectives, but the tests were mainly focused on the envelope materials. According to the different scenarios, the refurbishment of the two demonstrators had different scopes, so the tests carried out to determine the hygrothermal properties of the retrofitting materials were different for Cahors and Vitoria-Gasteiz.

4.2.1 Experimental work in Cahors

The thermal characterisation of the original bricks and stones in Cahors included: measurements of conductivity and thermal effusivity using the hot wire method, measurement of dry heat capacity using the calorimetric method, determination of the sorption isotherm by the Dynamic Vapour Sorption method (DVS), and measurement of water absorption by capillarity.

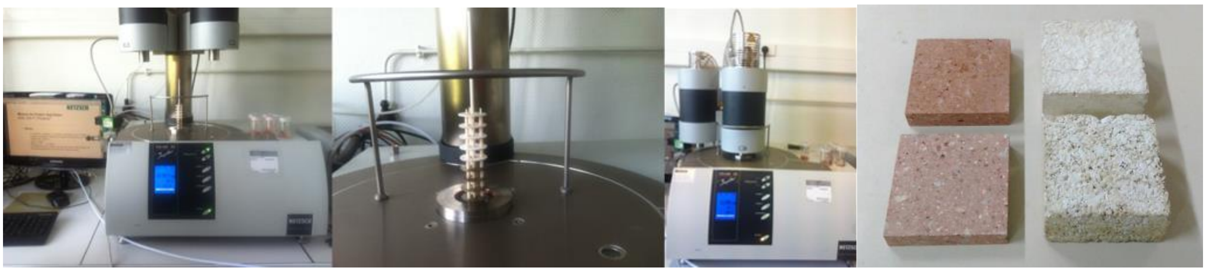


Figure 5: Measurement of the heat capacity by differential scanning calorimetry (left). 18th century brick (top left), 16th century brick (bottom left), CC1 (bottom right), CC2 (top right)

As explained in Section 4.1 the result of the co-design process was to select old vernacular techniques, made of bio-sourced materials. The physical properties of these traditional solutions (especially hygrothermal properties) were tested in the lab. Chosen solutions were then tested and enhanced in the university (mainly optimum mix ingredients and hygrothermal modelling) to be later settled in the real building in a workshop with a carpenter, an artisan, and a student (Figure 6).

Figure 6: Refurbishment of an external wall with apprentice craftsmen, source [56]

Two formulations of a lime-hemp mixture were characterised in the laboratory. The choice of formulations and samples of lime-hemp mixtures was made by a craftsman participating in the living lab. Given the difficulty of cutting the lime-hemp material, moulds the size of the desired specimens were made beforehand. The formulations studied are presented in Table 1 and are habitually used for establishment in bunch (formulation CC1) and coating (formulation CC2).

Table 1: Mass composition of the two lime-hemp mixtures studied for the demonstrator of Cahors

	CC1 (mass %)	CC2 (mass %)
Lime	33	31.5
Hemp	13	6
Sand	-	14.5
Water	54	47

The solutions were also carefully tested on-site before their application in the demo building [56].

4.2.2 Experimental work in Vitoria

As explained in Section 4.1, during the co-creation process for Vitoria a renovation based on insulation on the inside was chosen for the ground floor, and for the first and second floor two possible solutions were identified, both based on a renovation with thermal insulation applied on the outside: the first one based on cork panels and the second one based on lime and hemp mortar. For the latter, the influence of the process of application (manual or mechanical) was also studied, because it showed a big influence in the thermal conductivity of the material (related mainly to its density).

Figure 7: Cross-section of the refurbishment solution based on corkboard.

Table 2: Description of the solutions identified for the demonstrator of Vitoria-Gasteiz

Solution	Description	Comments
INS_0	4 cm of recycled cotton fibre insulation + 2 cm of natural gypsum board	Only for ground floor
LHC1	8 cm of lime and hemp coating	Manually applied, Density ≃ 1400 kg/m^3
LHC2	8 cm of lime and hemp coating	Mechanically applied, Density ≃ 800 kg/m^3
ETICS	External Thermal Insulation Composite System 2.5 cm of lime-based levelling mortar + 8 cm of corkboard + lime-based finishing coat (less than 1 cm), reinforced with fibreglass mesh	

Thermal conductivity measurements were carried out using the heat flow meter method (EN 12667:2001 [57]) and the thermal resistance of the materials applied to a base wall was determined using guarded hot box tests (EN ISO 8990:1994 [58]) (see Figure 8).

Figure 8: Sample and measurement equipment for thermal conductivity (top and medium left) and wall thermal resistance (top and medium right)

Complementary tests were also carried out, such as measuring the in situ thermal resistance of the building façade, or the resistance to water vapour diffusion of samples of lime and hemp mortar (Figure 9).

Figure 9: Thermal resistance measurement in situ (left) and samples for testing water vapour transmission properties (right)

Besides, the building in Vitoria-Gasteiz was monitored. The variables measured were temperature, relative humidity, heat fluxes through the envelope, and energy consumption to maintain conditions of comfort. To accurately measure energy consumption, electric heaters were used in empty dwellings. Additionally, CO2 sensors were installed in the occupied dwellings.

4.3 Numerical work

Simulations of historical buildings, with massive and heterogeneous walls, complex geometry and important natural airflow, are challenging [59]. Therefore, the objectives of the numerical work were adapted to the requirements of each case (occupancy and existing information mainly) using simplified indicators develop specifically for traditional buildings [60].

Previous studies [61] [62] have pointed out that the morphology of the historic urban environment changes the conditions at the outer limits of the thermal models, therefore the detailed modelling of the geometry of adjacent buildings was carried out to achieve consistent results.

4.3.1 Numerical work in Cahors

In the case of Cahors, the objective of this analysis was to study energy consumption, winter comfort, summer comfort and the risk of pathology development. The energy expenditure was due to the annual electrical consumption of convectors in kWh/m², which corresponds only to energy expenditure related to heating systems; the annual electricity consumption excluding heating systems and lighting, in kWh/m²; and annual electrical consumption of lighting in kWh/m². These three elements correspond to all electricity consumption. The summer comfort was described by the number of hours of discomfort during July and August, corresponding to the number of hours exceeding 27°C [60]. The risk of pathology development and winter comfort was described by the number of hours where the surface temperature was below 12.6°C [63].

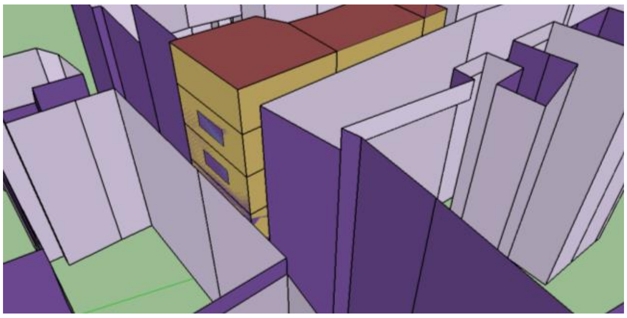


Figure 10: Demonstration building and surrounding masks - EnergyPlus

4.3.2 Numerical work in Vitoria-Gasteiz

The objective of the analysis in Vitoria-Gasteiz was to follow the evolution of the indoor temperatures of the different rooms and floors, to observe the correlation between the internal conditions, the external conditions and the intrinsic functioning of each thermal zone (power dissipation, occupation, ventilation, and shading). The temperature curve was taken to indicate the impact of these factors on the evolution of the temperature, or where the temperature peaks were found and to which phenomena they were related. Each simulated solution was analyzed to determine its impact and especially its relevance.

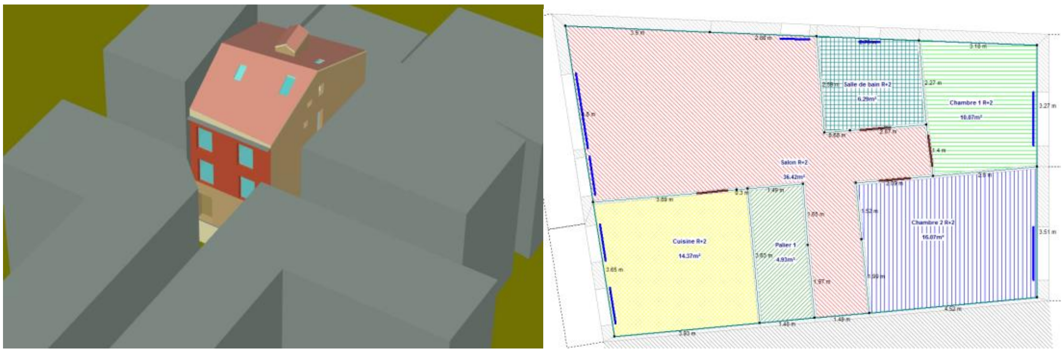


Figure 11: Demonstration building in Vitoria and surrounding masks

5 RESULTS AND DISCUSSION

5.1 Co-design process

As a result of the co-design process described in Section 3.1, the prototype demonstrator in Cahors was designed around the use of local lime and hemp for the interior and exterior envelopes of the walls and pressed wood fibre for the roof to be tested and monitored throughout the co-implementation stage. These solutions are produced in proximity (less than 100 km) and this was considered an opportunity to generate new business models based on the economy of scale engaging the agricultural sector of the region. Another advantage of these solutions was the fact that local craftsmen are used to implementing similar solutions. Unlike the situation in Cahors, in Vitoria-Gasteiz, it was not easy to identify a local material that could fulfil all the requirements since the territory had undergone profound transformations due to industrialisation. Therefore, the prototype demonstrator was conceptualised by integrating three different solutions for the interior and exterior envelope of the walls using lime hemp, lime and wood fibre, and lime and cork. Also, one solution was designed for the roof and one for the windows. The following table compares the two co-creation processes: the participants, the relevance of the different criteria and the co-designed solutions. The results of the AHP exercise were similar in both cities. The impact of the solutions on the cultural values was considered a priority in both cases as described further in the comparison of the two processes in Table 3.

Table 3: Comparison of the two processes

		CAHORS	**VITORIA-GASTEIZ**
WORKSHOPS			
Dates	**First workshop**	23/03/2017	30/03/2017
	Second workshop	6/04/2017	15/06/2017
Engaged Stakeholder	**Stakeholders facilitators of heritage refurbishment**	6 officials of Communauté d'Agglomération du Grand Cahors, refurbishment programmer	Ensanche 21 (Vitoria Municipal Council), Municipal Energy Agency (CEA)
	Local refurbishment industry	Confédération de l'artisanat et des petites entreprises du bâtiment (CAPEB)	ERAIKUNE (construction clusters of Basque Country)
	Research and innovation stakeholder	INSA laboratory (University of Toulouse), l'Association Sites & Cités Remarquables, PFT, QUERCY ENERGIE.	Santa María Cathedral Foundation, ENEDI laboratory (University of Basque Country), Tecnalia Research & Innovation.
CRITERIA/RELEVANCE			
Impact in heritage		**Very high relevance**	**Very high relevance**
Operational energy		**Very high relevance**	Medium relevance
Quality of life		High relevance	**Very high relevance**
Socio-economic development		Medium relevance	Medium relevance
Logistic easiness		Low relevance	Low relevance
Environmental impact		Medium relevance	Medium relevance
CO-DESIGNED SOLUTIONS			
Exterior envelope		Double layer on the existing masonry stone of the building, consisting of a first 7 cm wide layer made up of lime and hemp and a finishing layer of lime.	1st and 2nd floor: External Thermal Insulation System on the existing brick of the building, consisting of lime-based levelling mortar, corkboard and a finishing layer of lime.

Interior envelope	Double layer on the existing masonry stone of the building, consisting of a first, 20 cm wide layer made up of lime and hemp, and a finishing layer of lime, sand and hemp or lime and hemp.	Ground floor: A layer of recycled cotton fibre insulation and a finishing layer of natural gypsum board, put on the internal side of the existing masonry wall.
Roof	Double layer of rigid and semi-rigid wood fibre on wood board	Pressed wood fibreboard

5.2 Experimental work

5.2.1 Results of the experimental work in Cahors

The following table summarises the values measured and calculated before and after renovation in the building of Cahors. As can be seen in the table, for both walls, the addition of insulation reduced heat loss. The change is particularly noticeable for the initially very wasteful wood panel wall, where the thermal transmittance was divided by 5. For the brick wall, it was divided by 3.75. These solutions were selected for the demonstrator building.

Table 4: Measured and calculated heat transfer coefficients(U measured in-situ [W.m^{-2}. K^{-1}]; U calculated [W.m^{-2}. K^{-1}] with λ (16th century brick) = 0.49 W.m^{-1}.K^{-1} and λ (18th century brick) = 0.715 W.m^{-1}.K^{-1})

Material / Solution	**U value (measured in-situ)**		**U value (calculated)**	
	Before	**After**	**Before**	**After**
Brick	1.35	0.36	1.20 ± 0.07	0.43 ±0.04
			1.74 ±0.07	0.48 ±0.05
Timber frame	2.85	0.57	3.13 ± 0.09	0.55 ±0.07
			4.36 ± 0.1	0.57±0.07

5.2.2 Results of the experimental work in Vitoria-Gasteiz

In Vitoria-Gasteiz, the solutions that could be used in the demonstration building were tested in the Laboratory of Quality Control in Buildings of the Basque Government. The tests carried out provided information on the thermal behaviour of the following materials or refurbishment solutions: external coating of a mortar of lime and hemp applied manually, external coating of a mortar of lime and hemp applied by machine, wood fibreboard, and natural cork panel. As the hygroscopic properties are also important in historic buildings, in addition to the thermal tests, the resistance to the diffusion of water vapour was determined on a sample of lime and hemp. Two dwellings were tested to assess their air permeability. The air change rate values obtained at 50 Pa were 8.7 for the ground floor and 10.4 for the first floor. These values are very high so, if a ventilation system with heat recovery would be installed, concrete measures will have to be adopted to significantly reduce these values. The values obtained in the conductivity tests were:

Table 5: Conductivity values of the materials

Material / Solution	**k [W/m·K]**	**Comments**
Wood fibre board	0.045 ± 0.02	
Natural cork panel	0.059 ± 0.02	
Lime and hemp ($\rho \simeq 650$ kg/m^3)	0.13 ± 0.01	(Conditioned at 20ºC and 50% RH)
	0.12 ± 0.01	(Dried in oven at 70 ºC)

Two samples of lime and hemp coatings, with different methods of application to the wall, were tested in the laboratory. The results were quite different, mainly because of the difference in the water contents of the samples, which led to a marked density difference between the samples. The thermal resistance values obtained with the two samples are shown in the next table.

Table 6: Thermal resistance values of the tested solutions for Vitoria-Gasteiz

Material / Solution	**R [m2·K/W]**	**Comments**
8 cm of lime and hemp coating (LHC1)	0.24	Guarded hot box test. Manually applied, density ≃ 1400 kg/m^3
8 cm of lime and hemp coating (LHC2)	0.55	Guarded hot box test. Mechanically applied, density ≃ 800 kg/m^3
2.5 cm of lime based levelling mortar + 8 cm of corkboard + lime based finishing coat (ETICS)	1,65	Guarded hot box test.

Since LHC2 showed better thermal performance, its vapour diffusion resistance factor was determined by the test, to know the hygroscopic behaviour. The value obtained was $\mu = 19.3 \pm 2.8$, a value in the range of the lime-based materials.

Finally, the thermal transmittance of the two different façade solutions existing in the building was investigated in the in-situ tests. The values obtained and the improvement that would be achieved both on the ground floor (with INS_0) and in the first and second floor (with ETICS) are shown in the next table.

Table 7: Tested and predicted thermal transmittance values for Vitoria-Gasteiz

Material / Solution	**U [W/m^2·K]**	**Comments**
Masonry (Ground floor)	0.82	In situ test. Total thickness = 0.76 m.
Masonry + INS_0	0.43	Predicted value
Moulded brick wall + Fiberglass + Plaster (First floor)	0.46	In situ test. Total thickness = 0.36 m.
Moulded brick wall + Fiberglass + Plaster + ETICS solution	027	Predicted value

As mentioned above, the thermal characteristics of the tested solutions were all quite good, so other criteria, such as hygroscopic compatibility, were taken into consideration when the refurbishment solutions were selected.

5.3 Numerical work

5.3.1 Results of the numerical work of Cahors

For the thermal simulation of the demonstrator building of Cahors, the building was divided into three different dwellings: a co-working space (level 0 and 1), and two apartments to rent: a small one (for students at level 2) and a duplex flat (for a family at level 3 and 4, with a rooftop), and the energy consumption was simulated for each of them (Figure 12).

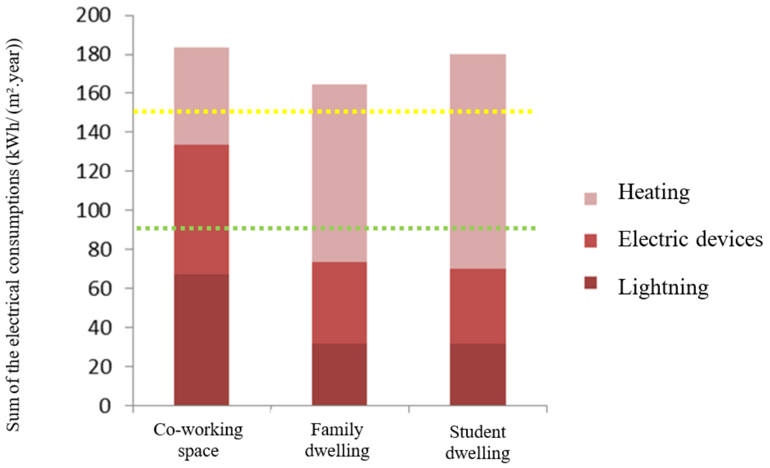


Figure 12: Energy consumption after refurbishment in Cahors

As expected, this numerical analysis nevertheless highlights a significant energy gain thanks to the different renovation systems in each of the spaces of the demonstrator building (see Table 8). For the three spaces, the simple change of windows from simple glazing to efficient double glazing reduces the electricity consumption related to heating by about ¼.

Table 8: Comparison of the energy gain (heating) according to the renovation technique and the spaces of the demonstrator building

	Energy-saving (reduction of the electrical consumption of heating)		
	Co-Working office	**Student dwelling**	**Family dwelling**
Double glazing	26.35%	23.78%	23.29%
Opaque wall insulation	44.65%	35.93%	35.88%
Attic insulation + double glazing + opaque wall insulation	71.15%	62.05%	62%

Despite the renovation, the co-working space keeps a cumulative amount of electricity consumption close to 150 kWh/m² due to the use of this space (lighting and electrical appliances). The occupancy and consumption scenarios were inspired by French thermal regulation, RT2012, and sometimes seem inappropriate, especially concerning the continuous use of lighting during hours of presence. The buildings studied have good summer comfort when not in use, i.e. without occupants, thanks to the reduction of the access of solar radiation and the inertia and strong contiguity of the buildings. No time of discomfort is noted during simulations without occupants, either before or after renovation. Calculations made with the occupant show that users play a decisive role as it has been mentioned by recent literature [31] [59]. Before the renovation, the internal loads due to electrical equipment and the occupant become too great in the upper part of the co-working space, and also in the upper north room of the family apartment (Figure 13).

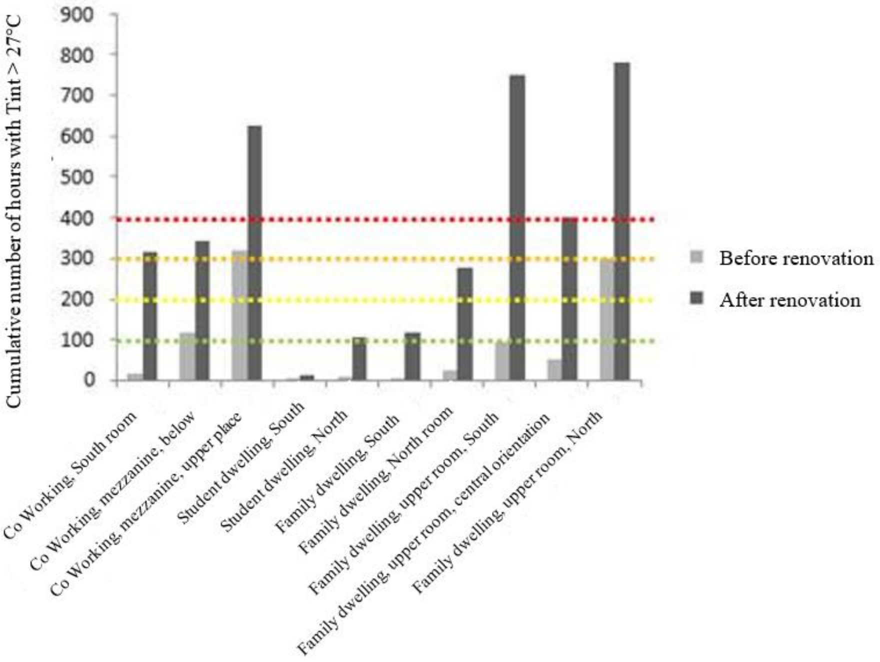


Figure 13: Number of hours of discomfort in use before and after renovation in Cahors

Thermal renovation, by accentuating the confinement, increases the number of hours of discomfort for each room. For low-volume rooms (southern part of the demonstrator building), this increase is particularly noticeable. However, in historic buildings, the limitation of existing main commercial thermal simulation softwares has to be considered, since they do not take the moisture buffering effect of walls into account, neither the effect of lime-hemp insulation in the improvement of the comfort by the regulation of the humidity of the room. The measurements carried out in situ after renovation, taken in combination with this numerical study and the study of the occupants' sensation of comfort, will make it possible to better evaluate the influence on the comfort of installing an interior, bio-based insulation.

5.3.2 Results of the numerical work of Vitoria-Gasteiz

In the case of Vitoria-Gasteiz before the renovation, the building was occupied only on the second floor and in the attic. The building envelope was not insulated, but windows in the occupied area were double-glazed from a previous renovation, the rest of the windows being single glazed. No heating system was present other than in the occupied part of the building. In this zone, the heating was managed by a gas boiler and the heat was emitted via wall heaters with hot water. The building was permanently heated to a set temperature of 21°C with a possible reduction to 19°C overnight. No mechanical ventilation was present. Except for the occupied part, no additional window opening to discharge the heat of the building and no management of mobile protections was considered. Although the unoccupied areas of the building were devoid of insulation and heating, a first study of the annual temperature curves showed that, by its structure, the building had good inertia (Figure 14).

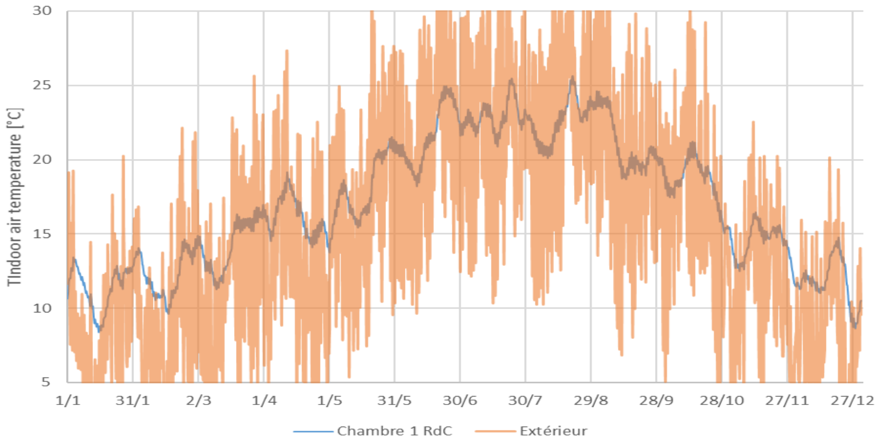


Figure 14: Inertia on the ground floor of the building in Vitoria-Gasteiz

The analysis of indoor temperature rise for increasingly high levels in the building shows stratification of air in the building, especially in the summer. In winter, it is noted that the temperatures of the second floor are lower than that of the first, which is suggestive of precarious insulation of the roof.

Table 9: The indoor temperature at several building levels in Vitoria-Gasteiz

	T° Min [°C]	T° Mean [°C]	T° Max [°C]
Kitchen second floor	10.6	19.5	32.5
Bedroom 2 second floor	9.5	18.5	28.3
Bedroom 1 first floor	12.5	18.6	25.2
Kitchen first floor	12.0	18.8	26.8
Kitchen ground floor	10.0	17.5	25.0
Bedroom 1 ground floor	8.4	17.1	25.7

For the building forecasts after renovation, the phase shift of the temperature and the limited variation of the temperature seen in the first results demonstrate that the thermal inertia of the building is always very good.

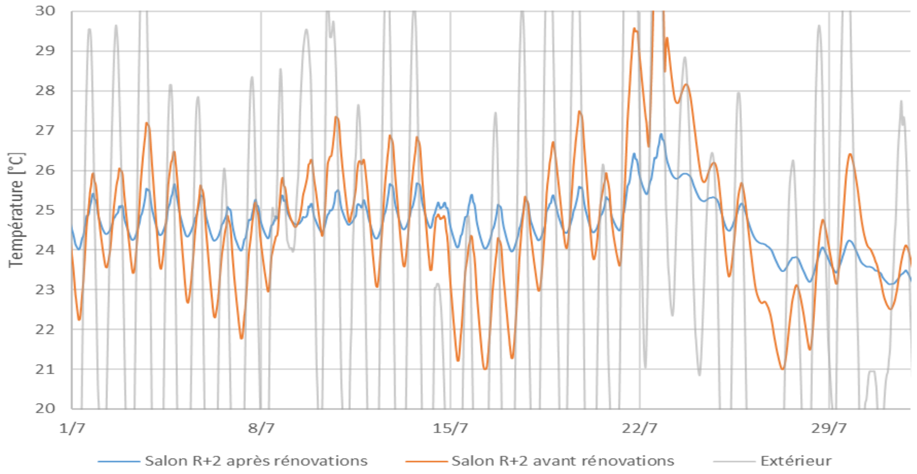


Figure 15: Comparison of temperature during July before and after renovations

Due to its more efficient envelope, the building is less sensitive to variations in the climate of Vitoria-Gasteiz. This allows it to exceed the temperature of discomfort a maximum of 5 times at most in the year, so the building can be described as comfortable.

In terms of energy consumption, if we compare what is comparable, namely the occupied part on the second floor, the energy-saving achieved is substantial. Although the implementation of controlled mechanical ventilation induces much higher electrical consumption, on an overall balance (that is to say, taking heating needs, DHW, ventilation, electrical appliances, etc. into account) the renovations will allow energy savings of more than 50%, as shown in Table 10. The efficiency of the building envelope allows almost 79% savings in heating. Once again, in-situ measurements will be carried out after this renovation, in addition to this numerical study, as a part of the co-creation process.

Table 10: Energy consumption before and after refurbishment in Vitoria-Gasteiz

	Before renovations		**After renovations**	
Zone	**Gas (PCS)**	**Electricity**	**Gas (PCS)**	**Electricity**
Heating	32 607 kWh	69 kWh	6 905 kWh	34 kWh
Domestic hot water	6 535 kWh	9 kWh	6 535 kW	-
Auxiliary ventilation units	-	-	-	2 040 kWh
Auxiliary distribution units	-	26 kWh	-	20 kWh
Power dissipated	-	2 794 kWh	-	2 794 kWh
TOTAL	**39 142 kWh**	**105 kWh**	**13 440 kWh**	**4 888 kWh**
ENERGY SAVING [Before – After]			**+25 702 kWh (+65.7%)**	**-4 783 kWh (-306.6%)**
TOTAL ENERGY SAVING			**+20 919 kWh (+53.3%)**	

6 CONCLUSIONS AND FUTURE WORK

The ENERPAT approach can be considered as a change in the way we see the energy improvement of historic urban areas and a step forward in the need to operationalise the vagueness of the concept of complexity in energy transitions. As previous research shows, the benefits obtained with this approach can support a systemic transformation of historic urban environments "*not only by improving its sustainability and liveability but also by reinforcing its local economy, preserving its cultural values and including all the stakeholders in the whole process*" [18]. This is aligned with place- based development, that suggest that development strategies should be based on mechanisms which "*build on local capabilities and promote innovative ideas through the interaction of local and general knowledge and endogenous and exogenous actors in the design and delivery of public policies* " [64].

The implementation of the approach has shown that the inclusion of more criteria than the usually considered cultural heritage and operational energy (such as LCA and socio-economic development) in the decision-making broadens the sustainability approach to include social and economic pillars. It also helps to identify traditional solutions that are locally produced so they have a smaller environmental impact and could trigger other processes beneficial for the citizens and the conservation of our cities, such the development of local economies (as the case of the hemp in Cahors).

The combination of the expertise and knowledge of the different profile of stakeholders (including heritage experts, craftsmen, end-users and knowledge partners) feeds the process providing different inputs and perspectives regarding the replicability (considering local techniques and skills), the economic and energy-saving potentials, the technical compatibility and the social acceptance of the proposed solutions. The partnership with local knowledge stakeholders (such as universities and research centres) allows the introduction of evidence-based considerations in the decision-making process and the customisation of the testing strategies fitted to the objectives, regulatory requirements and resources of each case.

The process has shown that the conservation-friendly bio-based solutions are an option that the key stakeholders identify as technically, economically, socially and culturally compatible with the historic urban landscape of their cities. The experimental and numerical work carried out showed good results also in terms of thermal behaviour in winter conditions. These solutions are recognised as efficient in the laboratory, and now the challenge is to see whether they are also efficient in real conditions, with real occupants' behaviour. Numerical simulations allow the theoretical behaviour of the buildings to be investigated in terms of comfort and energy consumption.

The flexibility of the method allows for implementation in different circumstances, as long as political long-term commitment is guaranteed to adopt an evolutionary strategy like the one described in this paper. Anyway, the cases of Cahors and Vitoria-Gasteiz show that it can be implemented gradually. Future work includes the implementation of the solutions in the representative buildings and their instrumentation to reveal the performance of these solutions in terms of summer indoor comfort, users' satisfaction, and hygrothermal behaviour. Other indicators should be also measured to monitor citizens' acceptance, fuel poverty decrease, energy reduction from an LCA perspective, and the creation of new business models at the urban level.

7 ACKNOWLEDGMENTS

This work was financially supported in the framework of the European project ENERPAT, Interreg SUDOE SOE1 / P3 / F0362 (Cocréation de solutions territoriales ENergétiquement efficaces d'Ecorénovation de l'habitat Résidentiel PATrimonial des centres anciens du

SUDOE). The authors would also like to thank to all the partners of the project for their contributions.

8 REFERENCES

[1] International Energy Agency and the United Nations Environment Programme. 2018 Global Status Report: towards a zero- emission, efficient and resilient buildings and construction sector. 2018.

[2] http://ec.europa.eu/environment/waste/construction_demolition.htm n.d.

[3] Todorović MS, Ećim-Đurić O, Nikolić S, Ristić S, Polić-Radovanović S. Historic building's holistic and sustainable deep energy refurbishment via BPS, energy efficiency and renewable energy—A case study. Energy Build 2014. https://doi.org/10.1016/j.enbuild.2014.11.011.

[4] Economidou M, Atanasiu B, Despret C, Maio J. Europe's buildings under the microscope. 2011.

[5] Gregório V, Seixas J. Energy savings potential in urban rehabilitation: A spatial-based methodology applied to historic centres. Energy Build 2017;152:11–23. https://doi.org/https://doi.org/10.1016/j.enbuild.2017.06.024.

[6] Egusquiza A, Prieto I, Izkara JL, Béjar R. Multi-scale urban data models for early-stage suitability assessment of energy conservation measures in historic urban areas. Energy Build 2018;164:87–98. https://doi.org/10.1016/j.enbuild.2017.12.061.

[7] Goldberg A, Leyden KM, Scotto TJ, Leyden KM, Goldberg A. Untangling what makes cities liveable: happiness in five cities. Proc ICE - Urban Des Plan 2012;165:127–36. https://doi.org/10.1680/udap.11.00031.

[8] Bradley D, Bradley J, Coombes M, Tranos E. Sense of Place and Social Capital and the Historic Built Environment. 2009.

[9] Egusquiza A. Multiscale information management for historic districts' energy retrofitting : a framework, a methodology, a model. Universitat Politècnica de Catalunya, 2015.

[10] Europe CO. European landscape convention. Rep. Conv., 2000.

[11] Boer J De, Zuidema C, Gugerell K. New interaction paths in the energy landscape: the role of local energy initiatives. Landsc Res 2018;43:489–502. https://doi.org/10.1080/01426397.2018.1444154.

[12] Jacobs J. The Death and Life of Great American Cities. New York: Random House; 1961.

[13] ICOMOS. The Washington Charter on the Conservation of Historic Towns and Areas 1987.

[14] Alexander C. A city is not a tree. City 1966;122:58–62.

[15] Salat S. Cities and Forms: On Sustainable Urbanism. Paris: CSTB Urban Morphology Laboratory; 2011.

[16] Winskel M, Markusson N, Jeffrey H, Candelise C, Dutton G, Howarth P, et al. Learning pathways for energy supply technologies: Bridging between innovation studies and learning rates. Technol Forecast Soc Change 2014;81:96–114. https://doi.org/10.1016/J.TECHFORE.2012.10.015.

[17] Butler C, Demski C, Parkhill K, Pidgeon N, Spence A. Public values for energy futures: Framing, indeterminacy and policy making. Energy Policy 2015;87:665–72. https://doi.org/10.1016/J.ENPOL.2015.01.035.

[18] Egusquiza A, Izkara JL, Gandini A. Energy efficiency improvement in historic urban environments : From decision support systems to co-creation strategies. 3rd Int. Conf. Energy Effic. Hist. Build., 2018, p. 576–84.

[19] Robertson Munro F, Cairney P. A systematic review of energy systems: The role of policymaking in sustainable transitions. Renew Sustain Energy Rev 2019:109598. https://doi.org/10.1016/J.RSER.2019.109598.

[20] Munarim U, Ghisi E. Environmental feasibility of heritage buildings rehabilitation. Renew Sustain Energy Rev 2016;58:235–49. https://doi.org/10.1016/j.rser.2015.12.334.

[21] Cantin R, Burgholzer J, Guarracino G, Moujalled B, Tamelikecht S, Royet BG. Field assessment of thermal behaviour of historical dwellings in France. Build Environ 2010;45:473–84. https://doi.org/10.1016/j.buildenv.2009.07.010.

[22] Martínez-Molina A, Tort-Ausina I, Cho S, Vivancos JLJL, Martinez-Molina A, Tort-Ausina I, et al. Energy efficiency and thermal comfort in historic buildings: A review. Renew Sustain Energy Rev 2016;61:70–85. https://doi.org/10.1016/j.rser.2016.03.018.

[23] Eriksson P, Hermann C, Hrabovszky-Horváth S, Rodwell D. EFFESUS Methodology for Assessing the Impacts of Energy-Related Retrofit Measures on Heritage Significance. Hist Environ Policy Pract 2014;5:132–49. https://doi.org/10.1179/1756750514Z.00000000054.

[24] Webb AL. Energy retrofits in historic and traditional buildings: A review of problems and methods. Renew Sustain Energy Rev 2017;77:748–59. https://doi.org/10.1016/J.RSER.2017.01.145.

[25] Thibodeau C, Bataille A, Sié M. Building rehabilitation life cycle assessment methodology–state of the art. Renew Sustain Energy Rev 2019;103:408–22. https://doi.org/https://doi.org/10.1016/j.rser.2018.12.037.

[26] Liu L, Li H, Lazzaretto A, Manente G, Tong C, Liu Q, et al. The development history and prospects of biomass-based insulation materials for buildings. Renew Sustain Energy Rev 2017;69:912–32. https://doi.org/https://doi.org/10.1016/j.rser.2016.11.140.

[27] Sovacool BK, Griffiths S. The cultural barriers to a low-carbon future: A review of six mobility and energy transitions across 28 countries. Renew Sustain Energy Rev 2019:109569. https://doi.org/10.1016/J.RSER.2019.109569.

[28] Colander D, Kupers R. Complexity and the art of public policy: Solving society's problems from the bottom up. 2014. https://doi.org/10.1111/gove.12292.

[29] Crawford R. What can complexity theory tell us about urban planning? 2016.

[30] Chilvers J, Foxon TJ, Galloway S, Hammond GP, Infield D, Leach M, et al. Realising transition pathways for a more electric, low-carbon energy system in the United Kingdom: Challenges, insights and opportunities. Proc Inst Mech Eng Part A J Power Energy 2017;231:440–77. https://doi.org/10.1177/0957650917695448.

[31] Berg F, Flyen A-C, Godbolt ÅL, Broström T. User-driven energy efficiency in historic buildings: A review. J Cult Herit 2017;28:188–95. https://doi.org/10.1016/J.CULHER.2017.05.009.

[32] Caro R, Sendra JJ. Evaluation of indoor environment and energy performance of dwellings in heritage buildings. The case of hot summers in historic cities in Mediterranean Europe. Sustain Cities Soc 2020;52:101798. https://doi.org/https://doi.org/10.1016/j.scs.2019.101798.

[33] Wu J. Urban ecology and sustainability: The state-of-the-science and future directions. Landsc Urban Plan 2014;125:209–21. https://doi.org/10.1016/j.landurbplan.2014.01.018.

[34] Levin S, Xepapadeas T, Crépin A-S, Norberg J, de Zeeuw A, Folke C, et al. Social-ecological systems as complex adaptive systems: Modeling and policy implications. Environ Dev Econ 2013;18:111–32. https://doi.org/10.1017/S1355770X12000460.

[35] Ostrom E. A general framework for analyzing sustainability of social-ecological systems. Science (80-) 2009. https://doi.org/10.1126/science.1172133.

[36] Geels FW. The multi-level perspective on sustainability transitions: Responses to seven criticisms. Environ Innov Soc Transitions 2011;1:24–40. https://doi.org/10.1016/J.EIST.2011.02.002.

[37] Rhodes A, Skea J, Hannon M. The Global Surge in Energy Innovation. Energies 2014;7:5601–23. https://doi.org/10.3390/en7095601.

[38] Sovacool BK, Furszyfer Del Rio DD. Smart home technologies in Europe: A critical review of concepts, benefits, risks and policies. Renew Sustain Energy Rev 2020;120:109663. https://doi.org/10.1016/J.RSER.2019.109663.

[39] Marshall S. Planning, Design and the Complexity of Cities. In: Portugali J, Meyer H, Stolk E, Tan E, editors. Complex. Theor. Cities Have Come Age, Berlin: Springer; 2012. https://doi.org/10.1007/978-3-642-24544-2_11.

[40] Bason C. Leading public sector innovationCo-creating for a better society. 2012. https://doi.org/10.1332/policypress/9781847426345.001.0001.

[41] Nevens F, Frantzeskaki N, Gorissen L, Loorbach D. Urban Transition Labs: co-creating transformative action for sustainable cities. J Clean Prod 2013;50:111–22. https://doi.org/10.1016/j.jclepro.2012.12.001.

[42] Frantzeskaki N, Wittmayer J, Loorbach D. The role of partnerships in “realising” urban sustainability in Rotterdam’s City Ports Area, the Netherlands. J Clean Prod 2014. https://doi.org/10.1016/j.jclepro.2013.09.023.

[43] Evans J, Karvonen A. Give me a laboratory and I will lower your carbon footprint! Urban Laboratories and the Pursuit of Low Carbon Futures. Int J Urban Reg Res (Guest Ed 2014;38:413–30. https://doi.org/10.1111/1468-2427.1207.

[44] Reimer MH, McCormick K, Nilsson E, Arsenault N. Advancing Sustainable Urban Transformation through Living Labs: Looking to the Oresund Region. 2012.

[45] Karvonen A, Evans J, Bulkeley H, Broto VC, Hodson M, Marvin S. Living laboratories for sustainability: exploring the politics and epistemology of urban transition. Cities Low Carbon Transitions, United Kingdom: Routledge; 2011, p. 126–41.

[46] von Hippel E. Democratizing Innovation. 2005. https://doi.org/10.1111/j.1540-5885.2006.00192_2.x.

[47] Gould JD, Lewis C. Designing for usability---key principles and what designers think. Proc. SIGCHI Conf. Hum. Factors Comput. Syst. - CHI ’83, 1983.

https://doi.org/10.1145/800045.801579.

[48] Chesbrough HW. The New Imperative for Creating and Profiting from Technology. 2003. https://doi.org/10.1111/j.1467-8691.2008.00502.x.

[49] Mitchell D, Coles C. The ultimate competitive advantage of continuing business model innovation 2003. https://doi.org/10.1108/02756660310504924.

[50] Rigillo M, Castagneto F, Gilchriest S. Environmental Performance of Urban Space: Rainfall Management in Sieti Village (SA). Civiltà delle acque. Passaro A., Napoli: Luciano; 2009.

[51] de Normalización y Certificación (1986- ...) AE. UNE-EN 13829:2002, aislamiento térmico, determinación de la estanquidad al aire en edificios, método de presurización por medio de ventilador. AENOR; 2002.

[52] ISO 9869-1 Thermal Insulation - Building Elements - In-situ Measurement of Thermal Resistance and Thermal Transmittance. Beuth; 2014.

[53] CEN European Commitee for Standardization. BS EN 16883 Conservation of Cultural Heritage—Guidelines for Improving the Energy Performance of Historic Buildings 2017.

[54] Nielsen AN, Jensen RL, Larsen TS, Nissen SB. Early stage decision support for sustainable building renovation – A review. Build Environ 2016;103:165–81. https://doi.org/10.1016/J.BUILDENV.2016.04.009.

[55] Saaty TL. Modeling unstructured decision problems — the theory of analytical hierarchies. Math Comput Simul 1978;20:147–58.

[56] Claude S, Ginestet S, Bonhomme M, Moulène N, Escadeillas G. The Living Lab methodology for complex environments: Insights from the thermal refurbishment of a historical district in the city of Cahors, France. Energy Res Soc Sci 2017;32:121–30. https://doi.org/10.1016/J.ERSS.2017.01.018.

[57] EN 12667: 2001 Thermal performance of building materials and products Determination of thermal resistance by means of guarded hot plate and heat flow meter methods - Products of high and medium thermal resistance. n.d.

[58] ISO 8990:1994 Thermal insulation — Determination of steady-state thermal transmission properties — Calibrated and guarded hot box n.d.

[59] Akkurt GG, Aste N, Borderon J, Buda A, Calzolari M, Chung D, et al. Dynamic thermal and hygrometric simulation of historical buildings: Critical factors and possible solutions. Renew Sustain Energy Rev 2020;118:109509. https://doi.org/https://doi.org/10.1016/j.rser.2019.109509.

[60] Héberlé E, Burgholzer J. Guidance for Finding a Sustainable Balance between Energy Efficiency, Comfort, Moisture Damage and Cultural Heritage Value in Historic Buildings. EECHB 2016 – Energy Effic. Comf. Hist. Build., Brussels: 2016, p. 52–58.

[61] Claude S. Étude expérimentale et numérique de solutions basées sur les éco-matériaux pour la rénovation thermique du patrimoine bâti urbain. 2018.

[62] Claude S, Ginestet S, Bonhomme M, Escadeillas G, Taylor J, Marincioni V, et al. Evaluating retrofit options in a historical city center: Relevance of bio-based insulation and the need to consider complex urban form in decision-making. Energy Build 2019;182:196–204. https://doi.org/10.1016/J.ENBUILD.2018.10.026.

[63] DIN 4108-2:2001-03 - Wärmeschutz und Energie-Einsparung in Gebäuden, Teil 2. Bauphysik 2001;23:178–9. https://doi.org/10.1002/bapi.200100970.

[64] Barca F, McCann P, Rodríguez-Pose A. THE CASE FOR REGIONAL DEVELOPMENT INTERVENTION: PLACE-BASED VERSUS PLACE-NEUTRAL APPROACHES*. J Reg Sci 2012;52:134–52. https://doi.org/10.1111/j.1467-9787.2011.00756.x.

9 ANNEX A – CONSTRUCTION DETAILS OF THE DEMONSTRATION BUILDINGS.

A.1 - CAHORS

Figure A.1 – General view of the building before refurbishment

Figure A.2 - View of the building during refurbishment

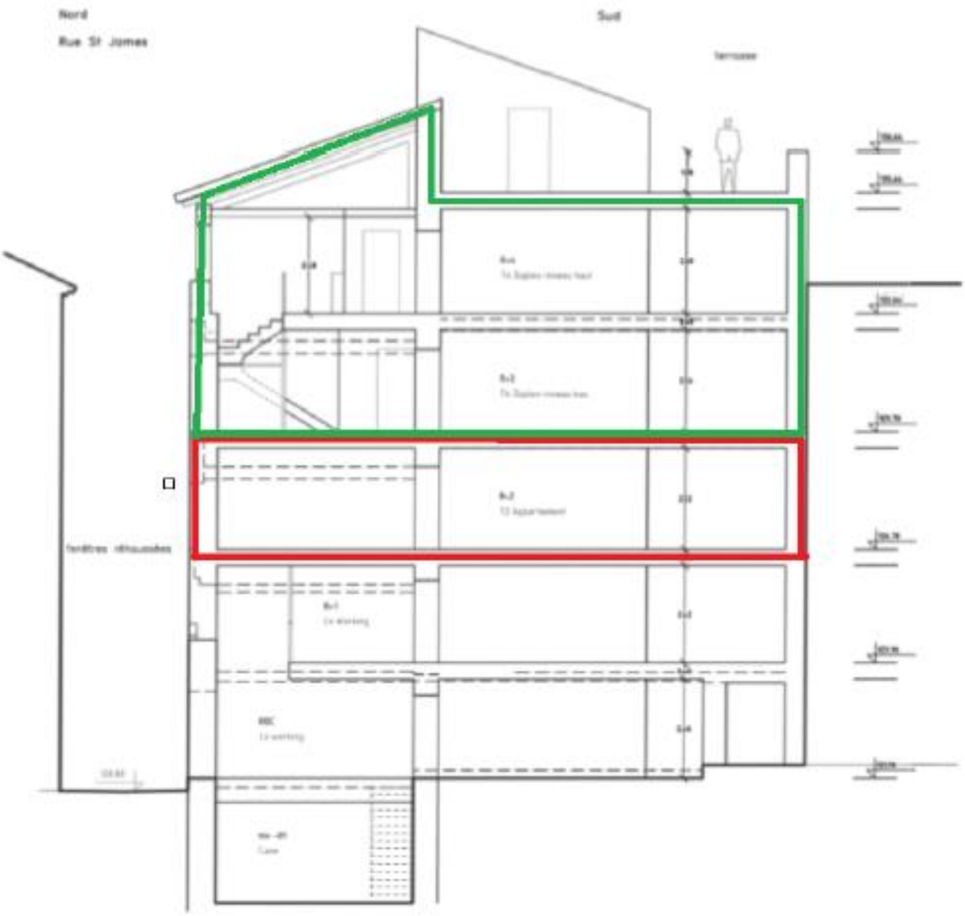


Figure A.3 - Longitudinal section of the building

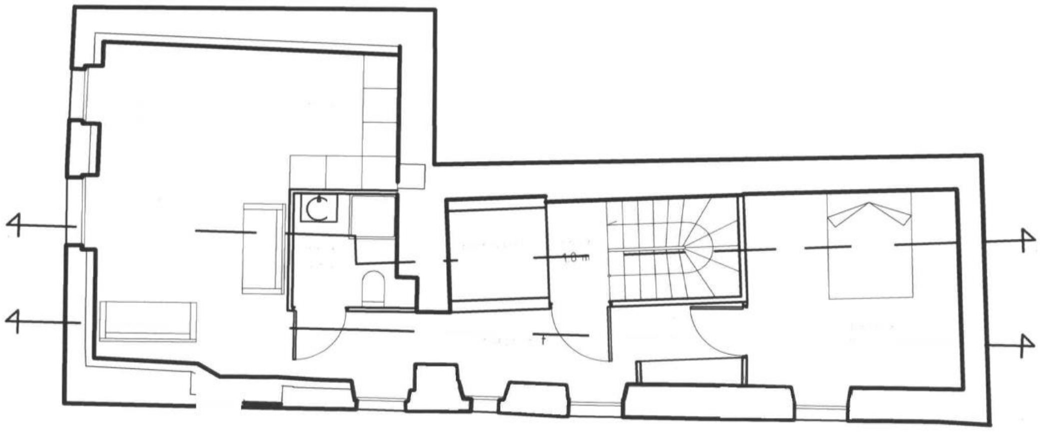


Figure A.4 - Cross-section of the building

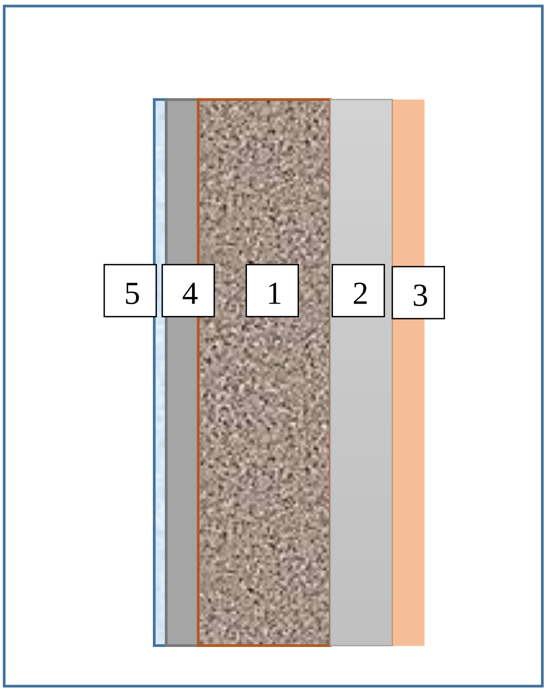


Figure A.5 – Materials used in the refurbishment of the demonstrator of Cahors

Legend: 1. Existing masonry ancient brick wall (about 40 cm), 2. Interior insulation layer: hemp concrete (20 cm), 3 Finishing layout (hearth, sand, gypsum) (about 5 cm), 4. Exterior insulation layer: hemp concrete (7 cm), 5. Outdoor finishing layout (hearth, sand, gypsum) (about 2 cm)

A.2- VITORIA-GASTEIZ

Figure A.6 - General view of the building before refurbishment

Figure A.7 - General view of the building after refurbishment

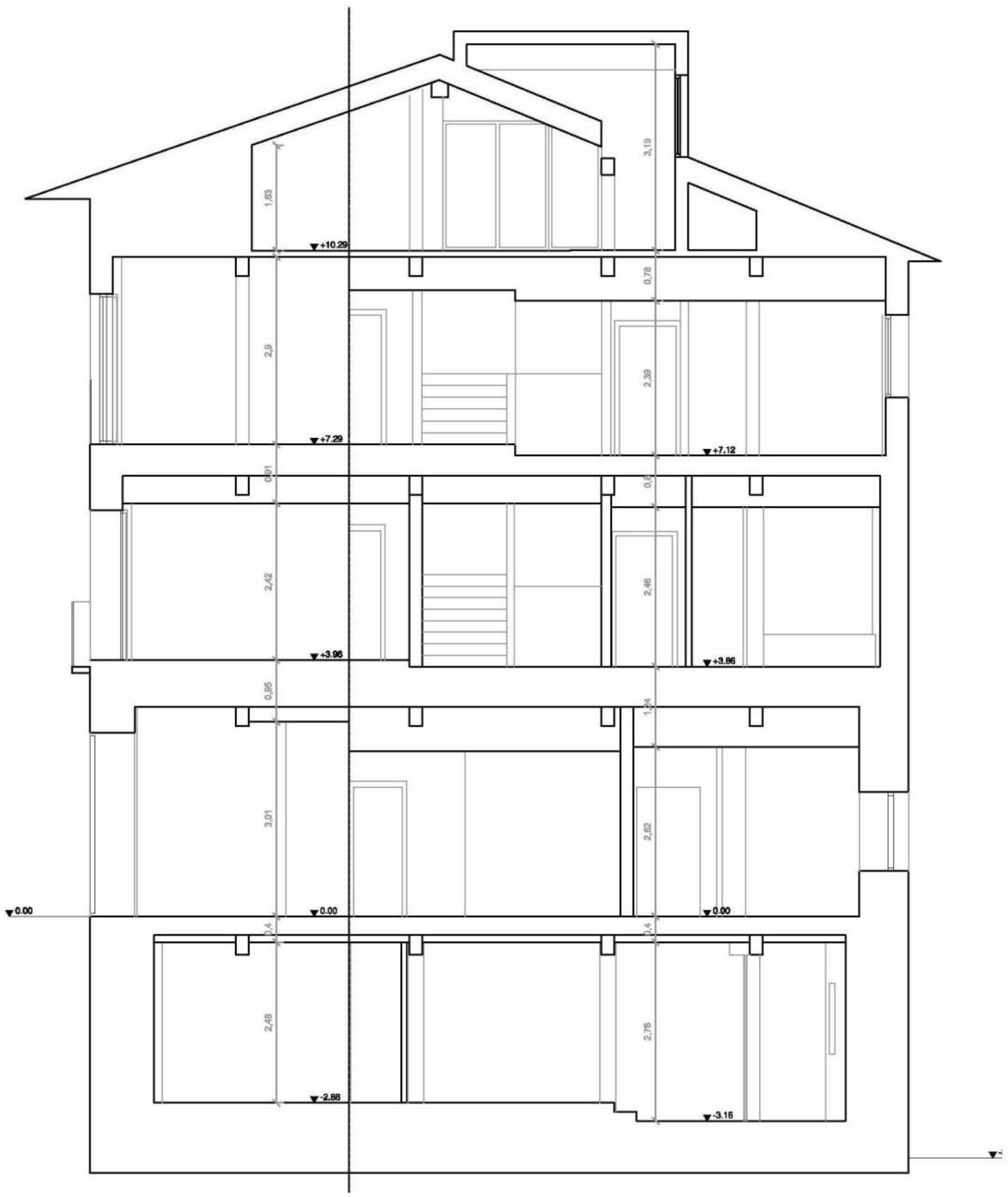


Figure A.8 - Longitudinal section of the building

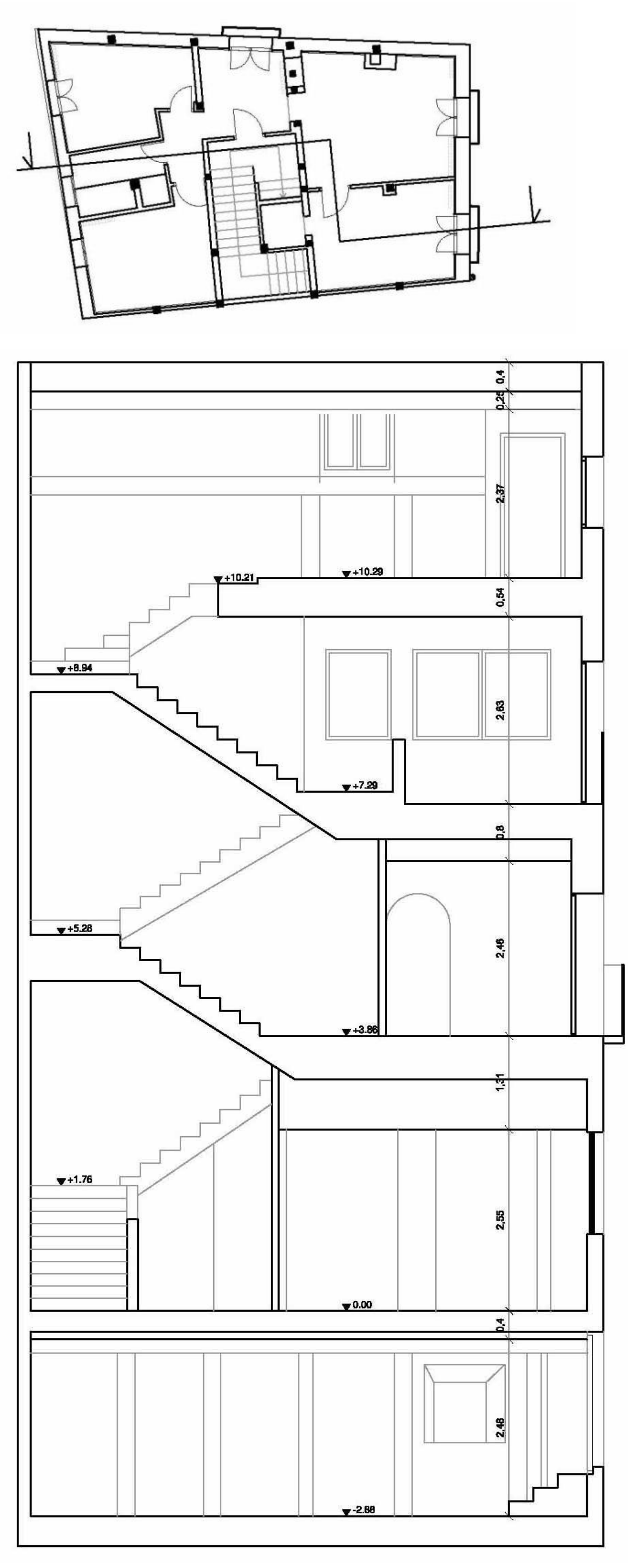
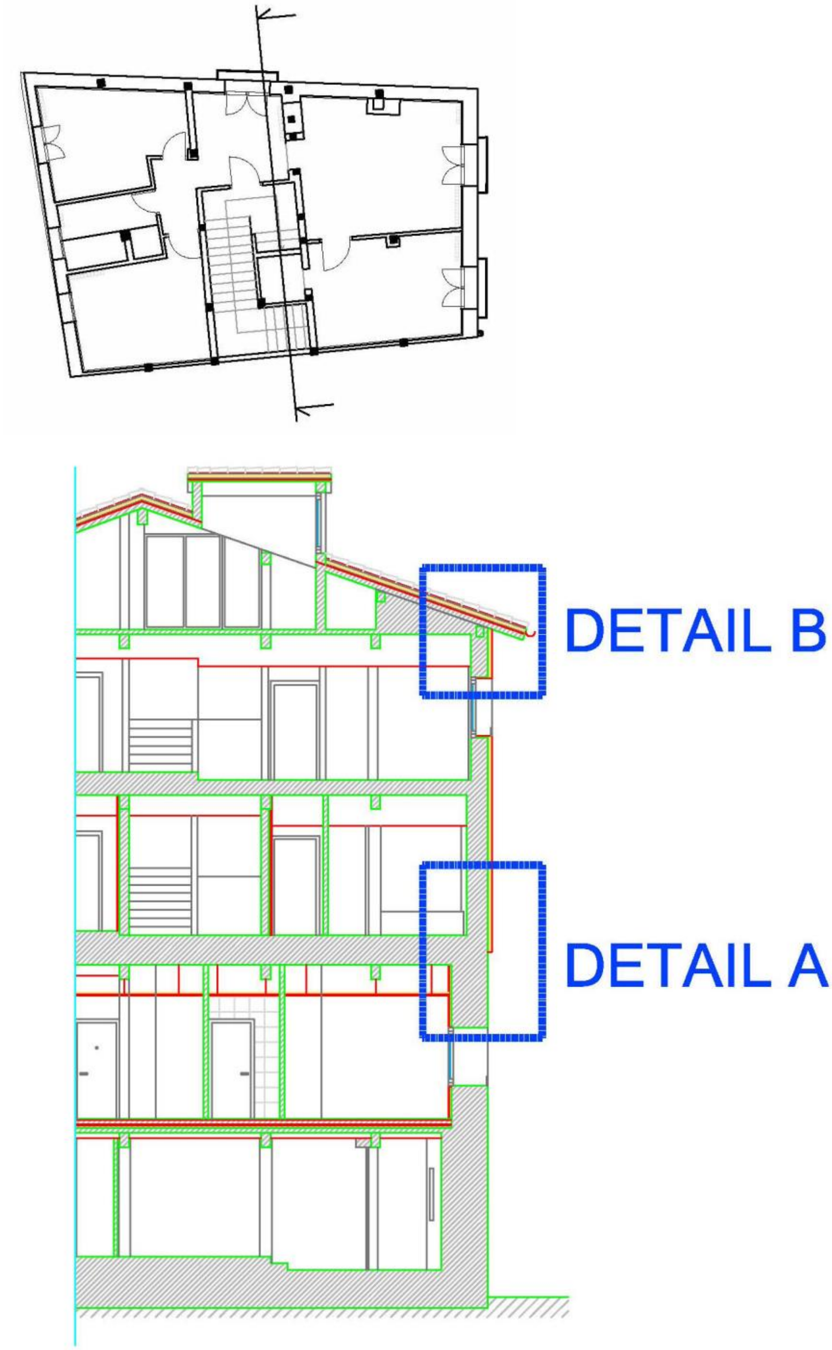


Figure A.9 - Cross-section of the building


DETAIL B
DETAIL A

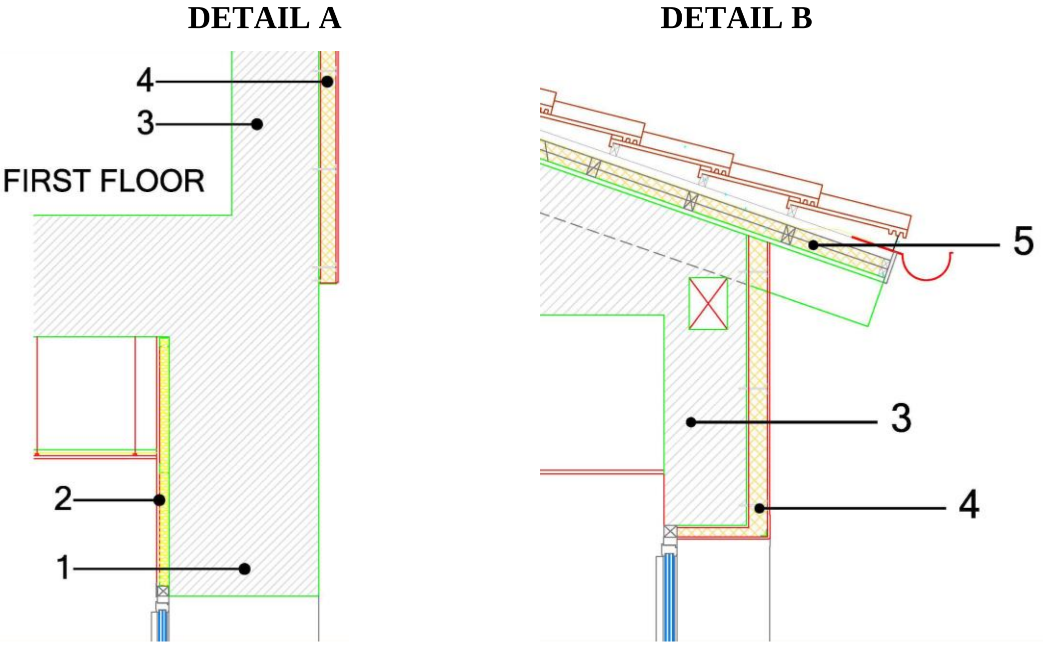


Figure A.10 – Materials used in the refurbishment of the demonstrator of Vitoria-Gasteiz

Legend: **1.** Existing masonry wall; **2.** Interior insulation layer: natural gypsum board (2 cm) and ecological Fiber Cotton panels (4 cm); **3.** Existing flattened brick wall (30 cm); **4.** ETIC Solution with cork panel (8 cm) and lime mortar; **5.** Pressed wood fibreboard under roof tiles (8 cm)

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

HIGHLIGHTS

- Energy efficiency of historic centres through eco-renovation and vernacular culture
- Energy transition based on co-creation and evolutionary development
- Urban labs to merge evidence-based knowledge with socio-economic considerations
- Architectural heritage is broadened to include traditional techniques
- Results of the co-creation process are tested with experimental and numerical work

Credit Author Statement

Egusquiza, A. : Conceptualization, Methodology, Validation, Investigation, Writing-Original draft preparation

Ginestet, S. : Methodology, Validation, Investigation

Espada, J.C. : Conceptualization, Methodology

Flores, I.: Methodology, Validation, Investigation

Garcia-Gafaro, C.: Investigation

Giraldo-Soto, C.: Investigation

Claude, S. : Investigation

Escadeillas, S.: Investigation