SUREFIT

SUstainable solutions for affordable REtroFIT of domestic buildings

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Other authors	**Aalto University (AALTO), Advanced Management Solutions Ltd (AMS), Instituto de Soldadura e Qualidade (ISQ)**

WP4 - Deliverable D 2.5

Results of technology sizing

Dissemination Level

PU	Public	**X**
CO	**Confidential, only for members of the consortium (including the Commission Services)**	
CI	Classified, as referred to in Commission Decision 2001/844/EC	

Document History

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2	24/03/2022	University of Nottingham	Final version for coordinator

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Abbreviations

SAHP	Solar assisted heat pump
GSHP	Ground source heat pump
TP	Thermal pipe
DX	Direct expansion
HWT	Hot water tank
DHW	Domestic hot water
COP	Coefficient of performance
GHE	Ground Heat Exchanger
ACH	Air changes per hour
DX SAHP	Direct expansion Solar assisted heat pump
PBP	Payback period
PCM	Phase changing materials
PV	Photovoltaic
PV/T	Photovoltaic thermal system
PV-VG	Photovoltaic vacuum glazing window
PVC	Polyvinyl chloride
SHGC	Solar heat gain coefficient
TP GSHP	Thermal pipe Ground source heat pump
WHR	Windows heat recovery

Publishable summary

The document reports a comprehensive assessment of technology sizing with energy, economic and indoor thermal comfort analysis which has been done in this stage for all the innovative technologies to be implemented in the five pilots buildings of the project.

Introduction

Leading Beneficiary: University of Nottingham (UNOTT)

Participants: Aalto University (AALTO), Advanced Management Solutions Ltd (AMS)

Task description:

This work package will involve development of models for simulating 1) flow of energy and associated phenomena and energy output for each technology, 2) energy flow in domestic buildings, 3) indoor environmental quality and 4) social acceptance of building retrofitting in order to optimise the technologies. Some numerical models will be developed based on commercial packages (e.g. CFD code Ansys Fluent) for fluid and heat flow modelling in PV vacuum glazing window, evaporative cooling and heat recovery devices and their integration within a building. Results will be obtained under different climatic conditions, including different solar radiation levels and ambient temperatures for heating and cooling modes. The optimal sizing of the technologies for different locations will be studied, taking into account energy outputs and the indoor environment as well as local culture. Results from this work package will also be used for the technology production (WP4). Completion of WP2 will be milestone 1. This work package will be carried out by all partners. AALTO is the leader of WP2 Task 4.2: Produce solutions for energy efficient facilities (UNOTT, M7-M17)

The document report the work regarding Task 2.5: Integration of technologies into a holistic solution for each building and climate (UNOTT and AALTO, M7-M15). A certain technical solution that enables energy efficiency may conflict with another in terms of indoor environmental quality and are socially acceptability. Therefore, it is important for UNOTT and AALTO to coordinate modelling and simulation to arrive a novel holistic integration solution and ensure consistent outcomes

Objective of D2.5: Integration of technologies into a holistic solution for each building and climate.

1 Summary

Buildings represent about 40% of the EU energy consumption, and 36% of the total CO_2 emissions. At present, about 35% of the EU's buildings are over 50 years old and almost 75% of the building stock is energy inefficient but only 0.4-1.2% of the building stock is renovated each year due to slow and costly renovation processes. The aim of this project is to demonstrate fast-track renovation (40% reduction in implementation time) of existing domestic buildings by integrating innovative, cost-effective, and environmentally conscious prefabricated technologies. This is to reach the target of near zero energy through reducing heat losses through the building envelope and energy consumption by heating, cooling, ventilation and lighting, while increasing the share of renewable energy in buildings. This will be achieved through a systematic approach involving key stakeholders (building owners and users, manufacturers, product and services developers) in space heating, cooling, domestic hot water, lighting and power generation, as well as a demonstration phase in five representative buildings in different climates.

A range of innovative energy efficient and cost-effective technologies are to be sized with optimum performance to reduce installation time and maintenance requirements, and increase reliability and affordability. By extension this will increase accessibility for all stakeholders from product manufacturers to building owners and users, which will have a wider impact in energy reduction across the EU. The technologies will include bio-aerogel panels and their integration with phase change materials (PCM), photovoltaic (PV) vacuum glazing windows, roof and window heat recovery devices, solar assisted heat pumps (SAHP) and ground source heat pumps (GSHP), evaporative coolers, integrated solar thermal and photovoltaic systems and lighting devices. The technologies are to be manufactured by the industrial partners of the project consortium and demonstrated under real-life context in five existing buildings under three different European (Mediterranean, Atlantic and North) climates to ensure their excellence in operation (Portugal, UK, Greece, Spain and Finland). Guidelines and effective operational tools will be developed for optimising the renovation process and decision making and an innovative business models will also be developed involving all factors affecting the total value of a property including its energy performance. Post retrofit, technologies installed will operate to maximise energy gain from renewable sources through smart controls while minimising heating, cooling and ventilation losses. Socio-economic analysis will then be done to assess how the installed measures impact the houses and district scales with respect to energy reduction in the thermal and electrical energy networks as well as occupants' satisfaction.

The technologies currently available for renovation are expensive and renovation processes are time consuming while disturbing the occupants, making it unattractive for deep retrofit to building owners. This project will make use of innovative modular/prefabricated technologies to rapidly renovate a selection of domestic buildings to reduce energy consumption not only from the existing levels but also to meet the aspiration for near zero energy buildings and meet personal comfort level. The innovative technologies will include novel ventilation leakage reduction methods such as membrane wrapping, envelope enhancement technologies such as bio-aerogel panel, PCM panel, PV vacuum glazing windows and surface coatings, and energy

efficient facilities including lighting/LED devices, passive heating and cooling strategies, innovative heat pump systems, roof and window heat recovery and solar thermal/ photovoltaics. The technologies will be adapted and optimised to different climate conditions and cultural and comfort standards.

Figure 1 shows a sketch of some technologies that are to be considered in renovating buildings in different EU member states. Some of the technologies illustrated will be suitable for specific climates and building types and so not all of the modules shown will be installed in a single building. The proposed project will involve the optimum sizing, manufacturing and demonstration of technologies for rapid renovation and performance monitoring in five buildings for three different climates. Key technologies for building renovation include i) bio-aerogel for insulation and PCM for passive heating/cooling, ii) heat pumps for space and water heating and thermal storage; iii) evaporative cooling, iv) PV/solar collector and PV vacuum glazing for windows, v) window heat recovery and vi) LED and light pipes.

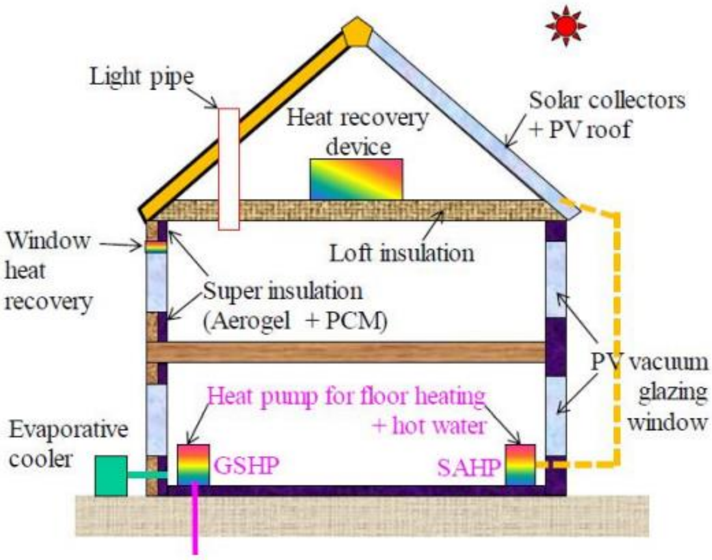


Figure 1 Illustration of proposed technologies for building retrofit

2 methods

2.1 Background

Building retrofit has long been considered, not only as the most effective approach to improve building energy efficiency, eliminate dependency on primary energy (natural gas, electricity) and reduce the associated carbon footprint but also as an evolving vehicle to continuously improve occupants' living standards (in the form of improved indoor comfort level, air quality and reduced noise level). These benefits, however, are not well articulated by policymakers and in building sectors and therefore are often not well received by the key stakeholders (i.e. homeowners, landlords, investors, SMEs). The obstacles to building retrofit are also multi-dimensional and vary largely according to the building typologies, energy usage by different occupants, and climatic conditions. For instance, the long and sometimes staged construction periods for building retrofits often disrupt the occupant's daily activities and even require the temporary evacuation of the property [1, 2]. Most importantly, the relatively high initial investment costs and associated long payback period (reported in the UK [3], Germany [4] and Denmark [5]), and the unpredictable economic benefits (due to the lack of detailed costs records and demonstrable bill saving potentials) are the major barriers to stimulate bottom-up building retrofits, which homeowners and investors might otherwise initiate.

In light of the above, European governments have introduced increasingly ambitious policies to promote building renovation and energy efficiency, supporting the goal of becoming climate neutral by 2050. Energy efficiency has seen a gradual improvement in the last decade. In the UK, for instance, social rented dwellings demonstrated the most prominent enhancements in energy efficiency. According to the 2019/2020 English Housing Survey [6], 60% of social rented dwellings managed by housing associations were rated between EPC A and C and 50% of local authority dwellings. In contrast, such an EPC range was only achieved by 29% of the dwellings occupied by homeowners and 33% in the private rented sector. Clearly, the ambitious goals and incentives initiated by the government have seen immediate impacts on the energy-efficient improvement for social housing. This is primarily since social housings are often managed by local city councils and large building associations, who are generally the pioneers to promote building retrofits at the urban scale. Unfortunately, there is still a large gap for promoting low-energy building retrofit in private-owned housings due to a lack of awareness of the associated benefits for key stakeholders and the various obstacles listed above. Because of the lack of an official European definition, Research [7] stated that the major 14 countries within the EU have an average annual renovation rate of 1.10%, with the range varying from 0.08% (in Spain) to 2.40% (in Norway). To overcome this, the implementation of deep building renovation with high-efficiency alternative measures are urgently needed, which help to transform existing properties into near zero-energy buildings with enhanced indoor environmental conditions. If appropriately addressed using a novel user-centred and bottom-up approach, these challenges in the private-owned housing sector could present enormous opportunities to encourage and stimulate wide adoption of building retrofit among key stakeholders. Therefore, it is urgent to understand the barriers and potential impact factors behind low retrofit rates and identify a multi-objective approach that aims to tackle the low-energy retrofit trilemma (i.e., energy efficiency, cost-optimality) the key stakeholders' perspectives) in a holistic manner.

To identify the optimal retrofit solutions, multi-objective optimisation is the most commonly employed method, as it enables the identification of trade-offs between the competing objective functions. In general, two mechanisms for optimising the building retrofit are mainly applied in the reviewed research [8]: the deterministic method (where the weighted sum method is often used) and the non-dominated method (Pareto front [9]).

The essential concept of multi-objective optimisation is Pareto optimality [9], which performs the optimisation performed by combining a building energy simulation software (Energy Plus) and an optimisation tool (a genetic algorithm written in MATLAB). This is a multiple criteria decision-making tool engaged with more than one objective function to be optimised simultaneously. However, all Pareto optimal solutions are acceptable without the subjective preference information, with less opportunity to interact with the stakeholders [10]. Moore et al. [11] proposed a community-level energy retrofit evaluation framework to determine Pareto optimal retrofit solutions for single-detached houses, which can be used to explore the trade-off between life cycle environmental and economic performances of building retrofits.

The Pareto method could achieve the visualisation of the trade-offs in retrofit planning, but several drawbacks have been highlighted:

1) It may not be appropriate to use the Pareto optimisation method when the homeowners' preferences conflict with the technical retrofit results, for example, the homeowners tend to have insufficient funding or lack of willingness to purchase the technologies that are optimised from the combinations [10].
2) Most previous studies [12-14] used mathematical models based on various assumptions. The assumptions used in quantitative models may not reflect real homeowners' motivations and preferences (such as self-living, rental or sale, and investment) in the decision-making process [15].
3) The decision-making of building retrofitting is a complex process involving numerous factors. However, most processes consider pre-defined and pre-evaluated intervention options/solutions [12]. Since this method often involves a minimal domain of renovation solutions, there is no guarantee that the final solution is the best from the decision-makers perspective. However, when a large domain of renovation solutions need to be defined and combined, this method becomes very complex and difficult to obtain meaningful results.

In order to correctly identify relevant parameters that can influence the selection of the retrofit technology, Seghezzi et al. [16] investigated several parameters based on a literature review, considering the building morphology, and employing interviews and discussions together with the actors involved in a building retrofit operation. These interviews were necessary to properly set the parameters and validate different points of view during the building process. Moreover, Chen et al. [17] also indicate that the final retrofit solution is not always a case of selecting the most cost-effective combination measures with the highest energy saving and lowest carbon emissions. Based on the survey conducted in the EU project RezBuild, the weighting factors (in the range of 0–1) representing various stakeholders' preferences were summarised. The energy, economic, environmental and social ranking factor (EEES) was calculated as the sum of the total multiplications between the various factors and the relevant weighting factors. Results concluded that stakeholder's satisfactions had gained increasing importance in measuring the success of projects, under the constraints of "iron" triangle: time, cost and quality.

Hence, to ensure that the model constraints are satisfied and the conflicting objectives are optimised simultaneously, the weighted sum method [18] is applied to transform the original problem into a single objective optimisation problem, where the decision makers' preferences could be involved by determining the multi-objective criteria and transform the output of each sub-objective function at the same scale. Moreover, to drive the building renovation agenda towards a user-centric manner, optimisation models specifically designed for the homeowners' involvement with different motivations need to be developed [18]. The objective functions can also be combined into one scalar function by applying constant weighting factors. This enables the benefits of conducting building renovations (such as energy bills, energy certification, discounted payback periods, initial investment cost) to be well articulated for various stakeholders, offering great flexibility and robustness to make relevant decisions decision-makers. Therefore, it is crucial to establish a practical and user-friendly multi-objective optimal approach to capture homeowners' preferences on proposed retrofit solutions and their combinations, as this could greatly facilitate the final decision-making process.

The "Cost-effective" method was suggested by the European Directive on the energy performance in buildings (EPBD)[1], with the definition of "the energy performance level which leads to the lowest cost during the estimated economic lifecycle, produced in a medium or long term(15–30 years)". Therefore, the objective of this research is to relate the global cost of each individual renovation measures with the primary energy consumption. The best "Cost-effective" measures will be those with the highest levels of energy savings and lowest capital investment.

The concept of cost-effectiveness is based on comparing the overall costs and (priced) savings of a potential action - in this case, of introducing a particular level of minimum energy performance requirements for buildings. In general, a measure or package of measures is cost-effective when the life cycle costs are lower than the value of the benefits that result over the expected life of the measure. Future costs and savings are discounted, with the final result being a "net present value". If the "net present value" is positive (NPV>0), the action is "cost-effective" (for the particular set of assumptions used in the calculation). This method can help us to determine the payback year with a certain technology package, according to the initial investment, operation cost, and energy saving bills.

Therefore, the calculation and analysis of the cost-effectiveness of a determined retrofit package will allows validation of breakthrough technology in the renovation of existing buildings, and so triggers wide use of these systems to improve building efficiency and given length of time since the built of the house.

In this deliverable (D2.5), the investment costs of the innovative measures are quoted according to the current market price. Cost-effective analysis for the 5 building pilots were carried out, based on final detailed refurbishment packages proposed by the project designer AALTO university, University of Nottingham, ISQ and all building residents. The costing figures used for analysis, will be changed according to the detailed site conditions and materials consumptions, and the final output will be used as the guidance for profitability analysis.

In this deliverable, the following procedures have been identified in order to give a first-hand estimation of the economic analysis for the demonstration building in all 5 building pilots:

1) According to current demo building conditions, retrofit regulations, and occupants' requirements, various technologies have been selected and combined as a holistic retrofit strategy.
2) These combined technology packages have been modelled in ICE-IDA software, which provides us with the detailed final annual primary energy consumption of electricity, natural gas and other heating sources.
3) Based on different energy price rates and feed in tariffs, the actual energy costs for each technology combinations can be calculated. These energy costs will be served as the input for the total energy cost.
4) The costs of each innovative measures will be determined based on the input data provided by both project partners and open market. Hence, the investment costs, maintenance and replacement costs will be calculated accordingly for each technology combination.
5) Finally, the investment costs, global costs and payback period could be calculated based on all the results obtained in the previous steps.

2.2 Objectives of the retrofit project

The contribution of SUREFIT to the expected impacts as listed in the LC-SC3-EE-1-2018-2019-2020: Decarbonisation of the EU building stock: innovative approaches and affordable solutions changing the market for buildings renovation is summarised as follows:

1) Primary energy savings by 60%, reduction of the greenhouse gases emissions by 60% and high energy performance in the renovated buildings.
2) Reduction of time needed on site for renovation works by at least 40% compared to current national standard practice using modular structures to be produced.
3) Measurable cost reduction compared with a typical renovation by 50% and a payback period below 10 years.

2.3 Analysis method

The approach of the project is first to sizing with optimum performance energy efficient innovative technologies for rapid renovation of domestic buildings. The technologies will then be evaluated under both controlled laboratories under real building conditions on technically, economic, environmental and social aspects

• Sizing of the proposed technologies (WP2). Individual energy efficient innovative technologies and combination of innovative technologies for retrofitting a building will first be optimised and their sizes determined based on three criteria – to provide a comfortable indoor environment, to reduce energy use and to be cost effective so that the technologies will be affordable from production, installation to operation and rapid for installation.

• Fabrication and laboratory testing of the technologies for retrofitting (WP4). The technologies will be produced and tested under controlled conditions. The conditions will simulate any climate where a building will be retrofitted. The key technologies will include bio-aerogel panel, PV vacuum glazing, integrated heat pumps, heat recovery device and evaporative coolers. Laboratory testing results will be used to modify and improve the design. Meanwhile control strategies and hardware for the operation of technologies will also be developed for optimum performance (WP3).

• Retrofitting of buildings and demonstration of the performance of the technologies and buildings under real life context (WP5 and WP6). The technologies produced and tested will then be integrated into five buildings in five countries (Finland, Greece, Portugal, Spain and UK). The energy use by the retrofitted buildings will be monitored for at least 12 months before retrofitting and 12 months after retrofitting to determine the amount of energy saving and carbon emission reduction after retrofitting. The buildings will also be demonstrated to visitors.

Assessment of life cycle economic, social and environmental impacts (WP7) and dissemination and exploitation of the technologies (WP8). In WP7 for best results, a methodology will be developed for planning and retrofitting of residential buildings. A method of generating a planning of building retrofit for a portfolio of buildings, in one aspect, may include receiving input information including at least retrofit costs, payback period specifying the length of time needed to recover the retrofit cost, the budget available for retrofitting action, expected price of energy, estimated energy savings and greenhouse gas emission reduction from retrofitting. The method may also include selecting an optimisation model based on an objective: maximising cost reduction and energy reduction, or both. The method may further include generating the planning of building retrofit based on the selected optimisation model and the input information. An example of optimisation model is illustrated in Figure 2. WP 8 the results from both laboratory and field tests will be used to assess the economic viability, environmental sustainability and social acceptance of the technologies. The assessment will make use of life cycle analysis. Innovative business model for the technologies uptake in the market will also be developed to address the cost-optimality aspect for given building types and geo-clusters across Europe. The outcomes of the project in terms of new products and IP relating to the technologies will be exploited by the industrial partners of the consortium. The acceptance of occupants and visitors will be assessed which will be used to update the social and economic analysis. Results will be disseminated to a range of audiences from academia to general public.

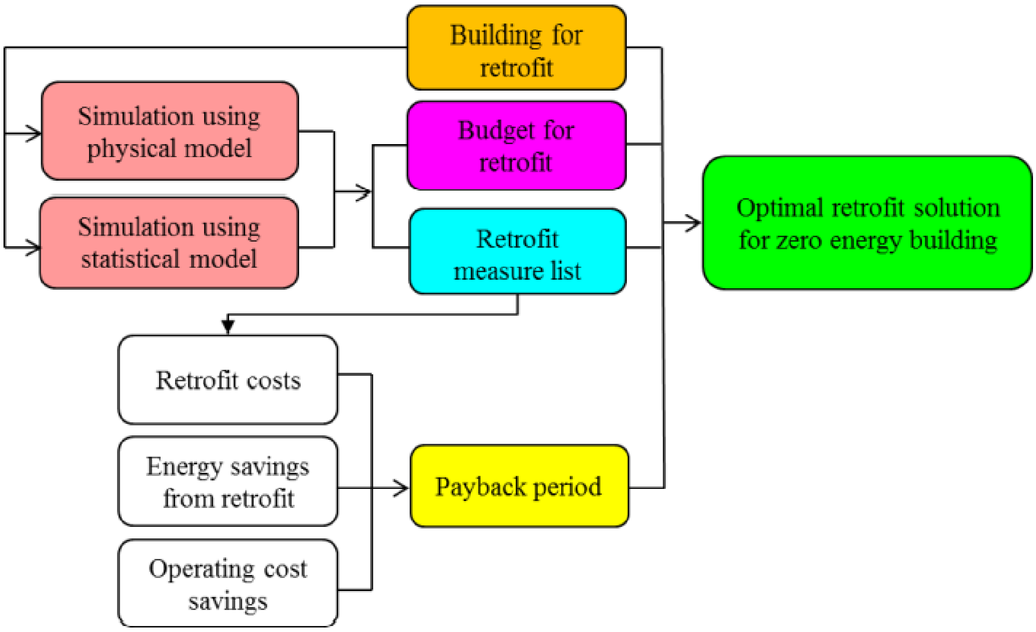


Figure 2 Flowchart of optimisation model

The following diagram – Figure 3 (BPIE, 2010)[19] summarizes the necessary steps to be followed when implementing cost-optimality at national level.

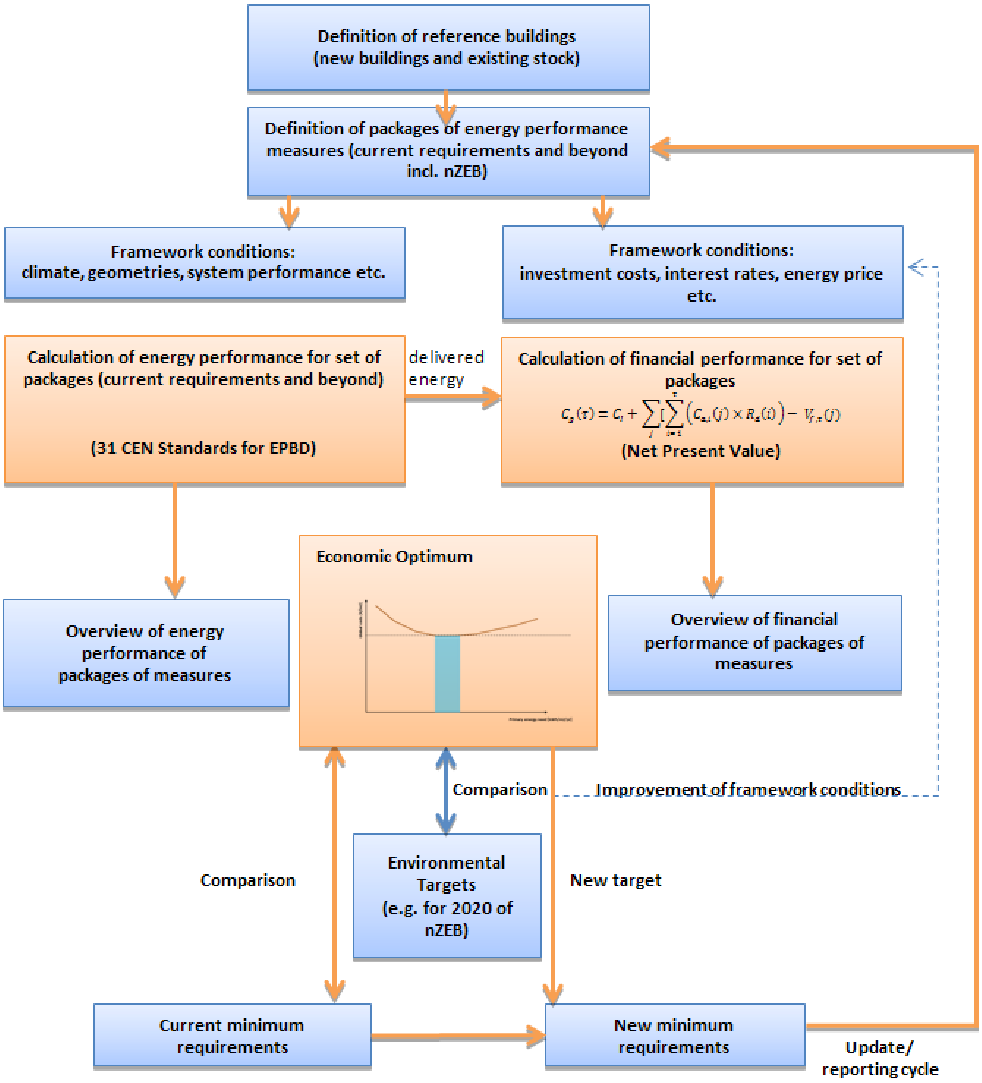


Figure 3 Implementation steps of cost-optimal methodology

(Source: BPIE, 2010)

After combining reference buildings with different packages of measures, the calculation splits into two: the calculation of the energy performance and the calculation of the financial performance of the different combinations of reference buildings and packages.

- Energy performance:

The energy performance calculations for the chosen combinations of reference buildings and packages can be performed with the help of ICE IDA modelling software that have been developed to support the modelling implementation of the retrofit process. Framework conditions for the calculations are climate data, performance of energy systems, etc.

- Financial performance:

To assess the financial performance of the chosen combinations, the global cost calculation method from the European Standards EN 15459 (Energy performance of buildings – economic evaluation procedure for energy systems in buildings) can be used. This method results in a discounted value of all costs during a defined calculation. The calculation of energy costs is thereby fed by the results of the energy performance calculations. Input data for the calculations are investment costs, interest rates, fuel prices etc.

A cost curve shows the assessed combinations of energy performance (x-axis) and financial performance (y-axis). It is this way that an economic optimum can be derived.

The relationship between current requirements and the position of the cost optimum is submitted to the Commission in a reporting cycle and can be used to update requirements, if suitable.

The comparison with future environmental targets could feed into a new loop, represented by the dotted line. This loop enables the effect of improved framework conditions (e.g. the introduction of soft loans) to be assessed, shifting the economic optimum towards medium- or long-term targets. Although not part of the EPBD recast, this loop could be used as a national steering tool.

3 Retrofit technology

3.1 Technical performance of all retrofit technologies

In the SUREFIT project, 9 retrofit measures are proposed as passive, active and renewables. Among them, 4 passive retrofit measures are included with PV vacuum glazing window (Figure 4), bio-aerogel insulation blanket (Figure 5), breath membrane (Figure 6) and PCM insulation panel. The main technical specifications are listed in Table 1.

Table 1 Technical specifications of the passive retrofit measures

Passive retrofit measure	Parameter 1	Parameter 2	Parameter 3	Parameter 4
PV Vacuum glazing window	U-value: 0.614 W/m^{2}K	Solar heat gain coefficient (SHGC): 0.178	Lighting transmittance: 50%	Solar power: 71.4W/m^2 under test standard of STC (1000W/m2 solar radiation, 25°C cell temperature)
Bio-Aerogel insulation blanket	K-value: 0.024 W/mK	Density: 43 kg/m^3	Specific heat capacity: 2260J/(kgK)	Moisture permeability: 65 GNs/kgm
Breathable Membrane	K-value: 0.029 W/mK	Density: 96.15kg/m^3	Airtightness: 0.16-0.18 m^3/hm^2	Vapour resistance: 0.11-0.40 MNs/g
PCM insulation panel	k-value: 0.21-0.23W/mK	Density: 765-1500 kg/m^3	Specific heat capacity: 2.2-2.42 kJ/kg K	Fusion heat capacity: 230-305 kJ/kg

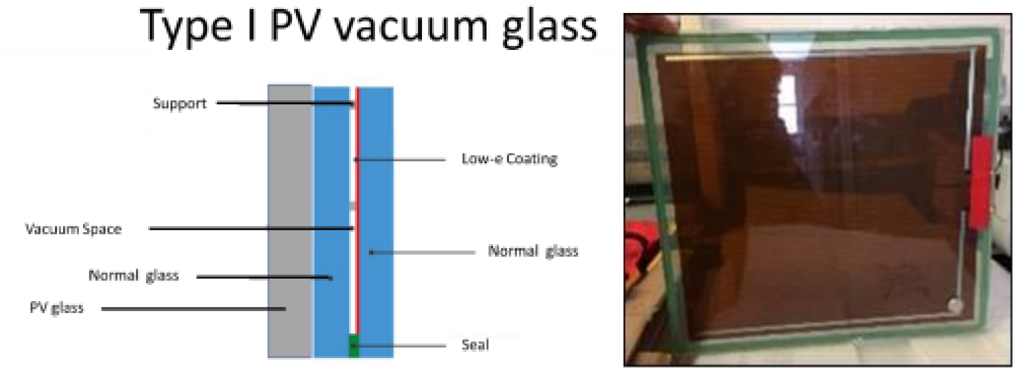


Figure 4 PV Vacuum glazing window

Figure 5 Bio-aerogel insulation blanket

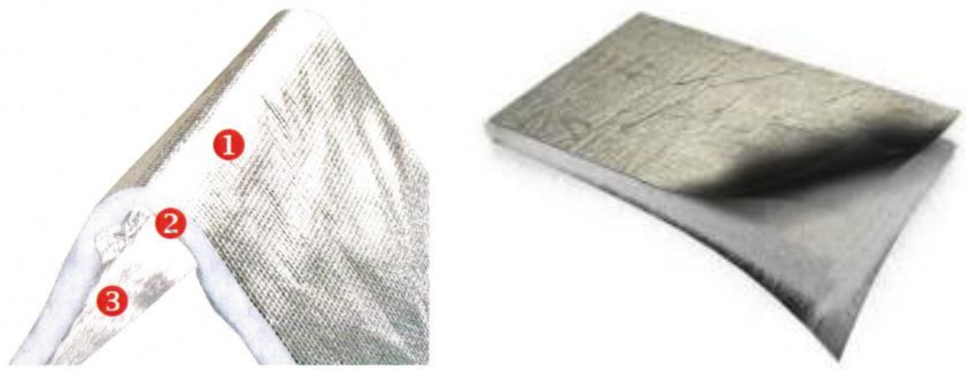


Figure 6 Breathable membrane

Figure 7 PCM insulation panels

Five active retrofit measures are proposed in the SUREFIT project with solar assisted heat pump, heat-pipe based ground source heat pump, evaporative cooler, window heat recovery and daylighting louvers. The technical specifications are described as below:

Solar assisted heat pump can supply space heating and generation of domestic hot water all in one system, which is combined by a compact core box and solar thermal dynamic panels (works as an evaporator). The SAHP system is connected to a hot water storage tank to provide both hot water and space heating for the occupants, as shown in Figure 8. The solar thermal dynamic panels could be installed on roof top, vertical walls, as shown in Figure 9. The heat source comes from both ambient air and solar radiation.

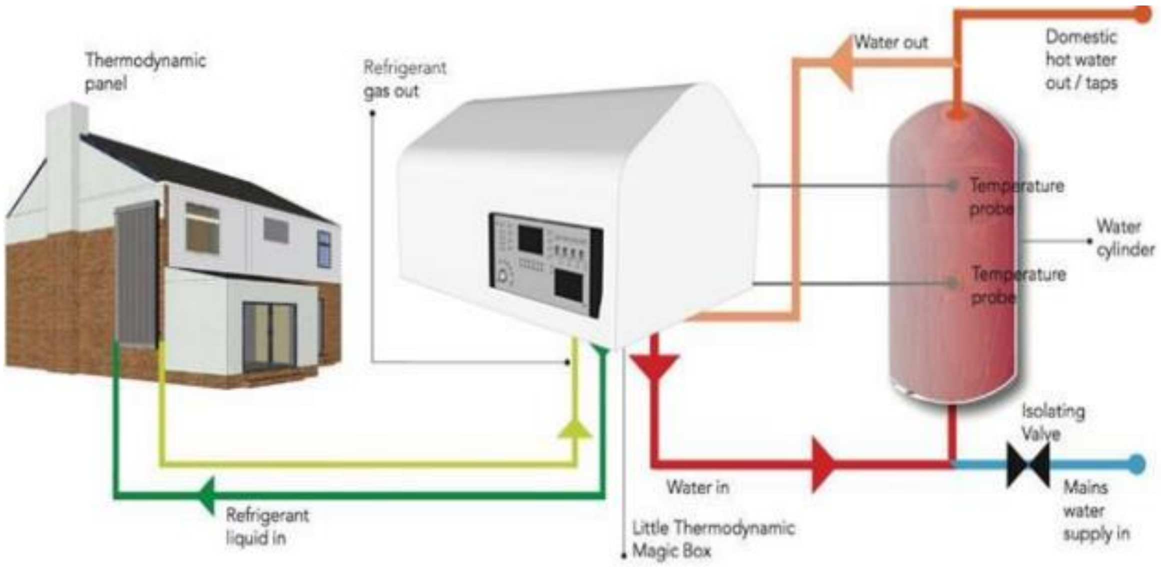


Figure 8 SAHP system working flows

Figure 9 Installation positions of the thermodynamic panels

The overall system COP is related to the plate temperature which is given by:

$$T_p = (1 - F_R)\left[T_a + \frac{\eta_{opt} G_t}{5.7 + 3.8V_a}\right] + F_R T_3$$

Where,

- T_p – plate temperature of the thermodynamic panel (ºC)
- T_a – environment temperature (ºC)
- T_3 – evaporator inlet temperature (ºC)
- F_R – ratio between actual power output and power output when (0.85)
- V_a – wind speed (m/s)
- G_t – solar radiation (W/m^2)
- η_{opt} – optical efficiency of the solar collector (0.9)

Therefore, according to the COP formulation, the detailed relationship between COP and the plate temperature of the thermodynamic panel - T_p is calculated for the 4 building pilots in the UK, Greece, Spanish and Portugal, as shown in Figure 10, Figure 11, Figure 12 and Figure 13. In

Finnish pilot, the outdoor air temperature is too low to maintain the well operation of the thermodynamic panels. Therefore, we do not consider the application performance of the SAHP system in Finland.

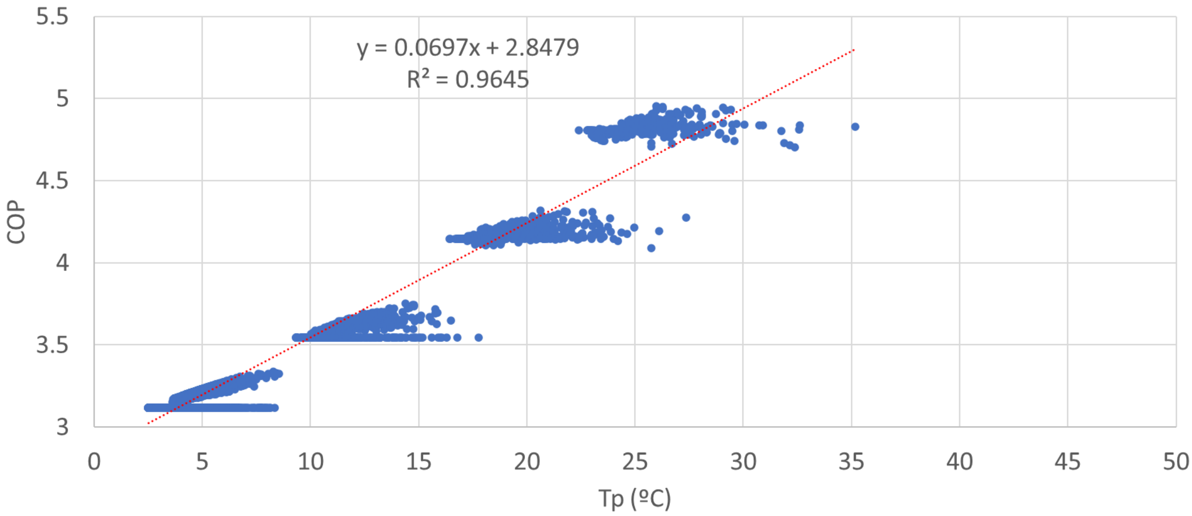


Figure 10 Relations of COP and T_p in the UK pilot

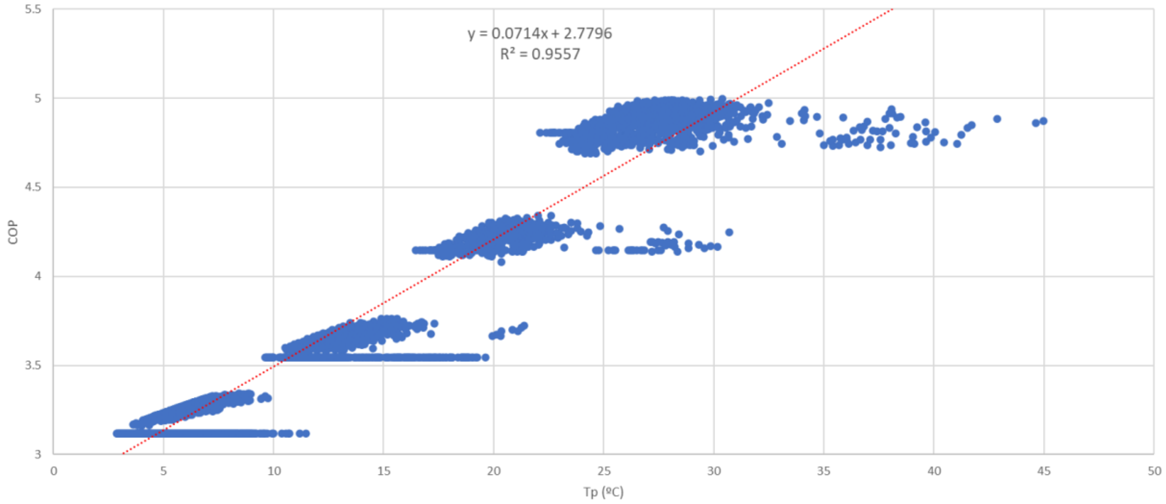


Figure 11 Relations of COP and T_p in the Greece pilot

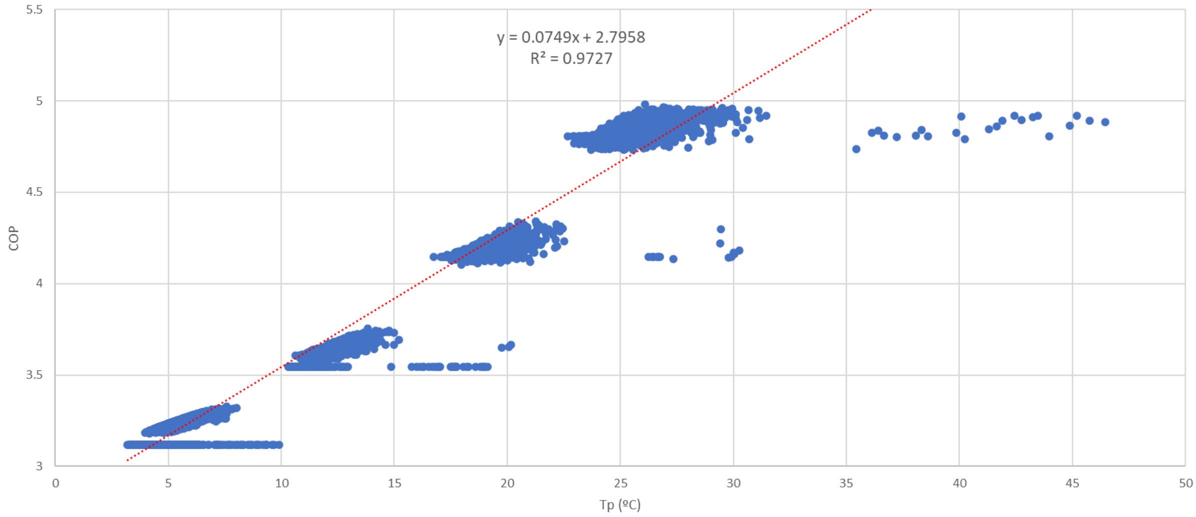


Figure 12 Relations of COP and T_p in the Portugal pilot

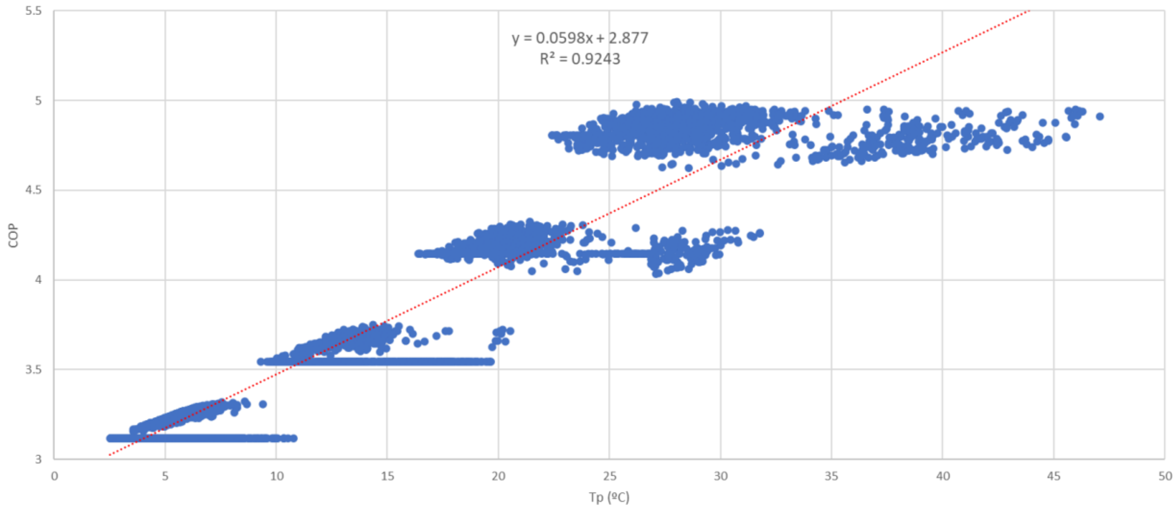


Figure 13 Relations of COP and T_p in the Spain pilot

Moreover, the daily system COP according to the local weather conditions are also calculated which could be used in further energy performance calculation, as shown in Figure 14-Figure 17. The maximum/minimum system COP, maximum system power input and seasonal system COP of the four pilots are listed in Table 2.

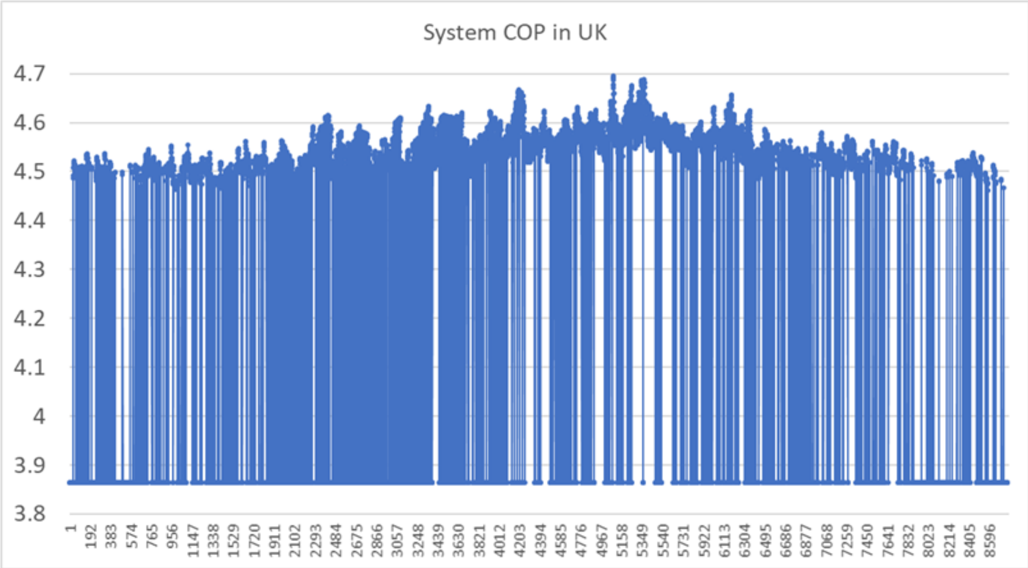


Figure 14 Daily System COP in UK pilot

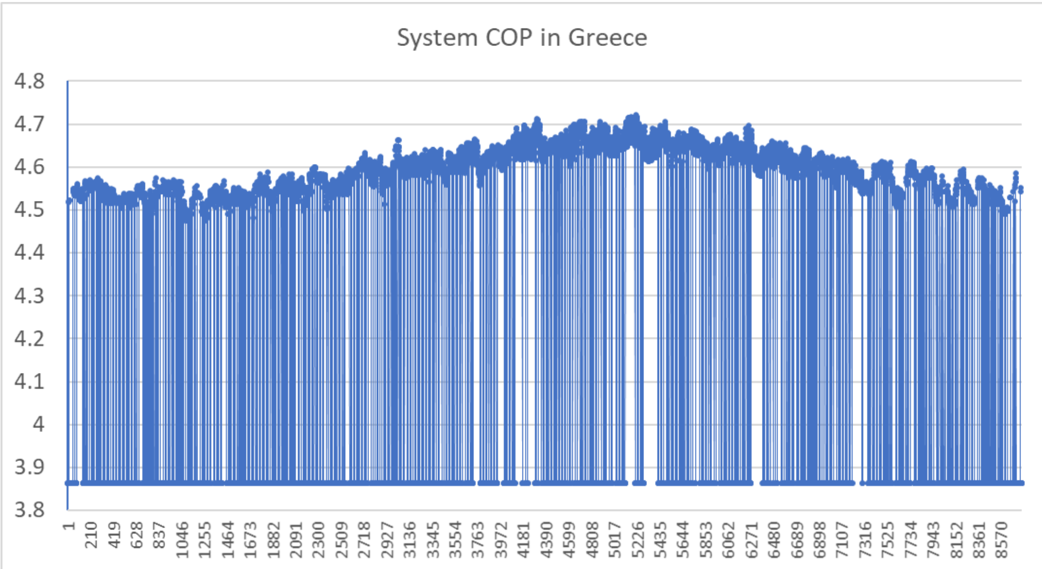


Figure 15 Daily System COP in Greece pilot

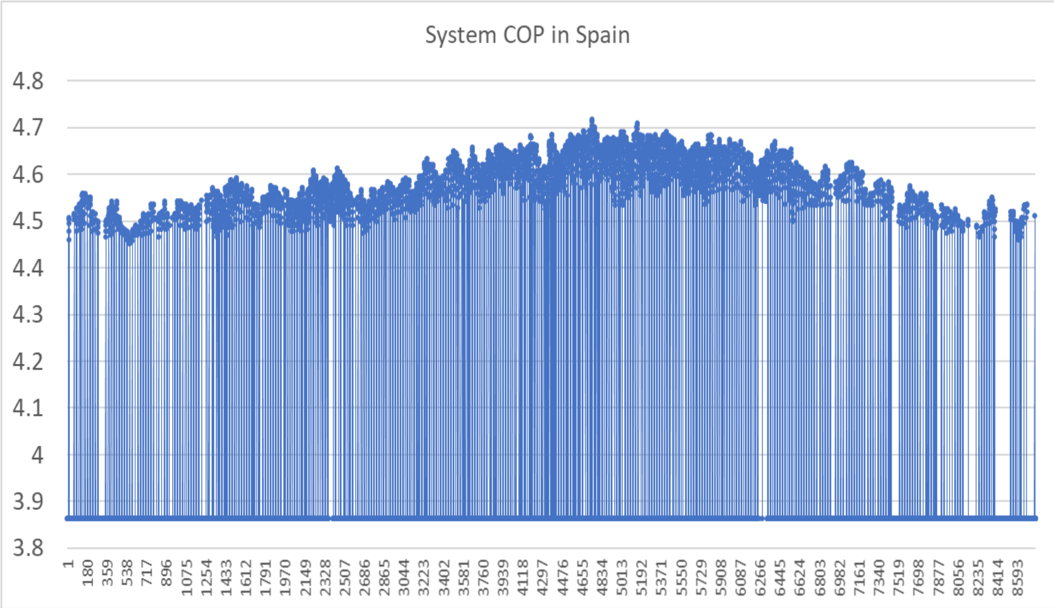


Figure 16 Daily System COP in Spain pilot

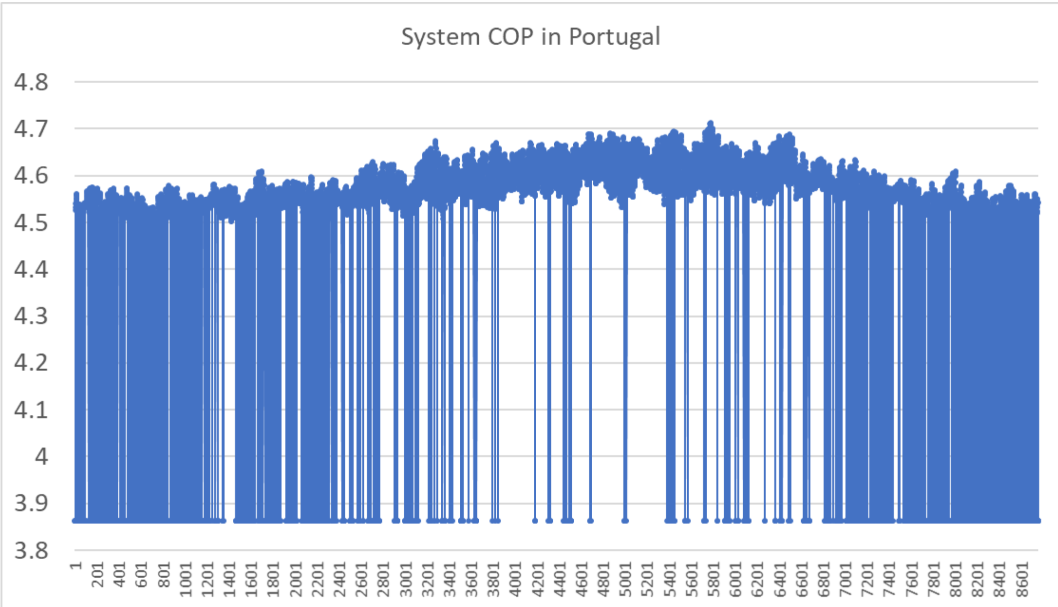


Figure 17 Daily System COP in Portugal pilot

Table 2 Summarized COP and power input of building pilots

	UK pilot	Greece pilot	Spain pilot	Portugal pilot
Maximum system COP	4.70	4.72	4.72	4.71
Minimum system COP	3.86	3.86	3.86	3.86

maximum system power input	750W	924W	1150W	893W
seasonal system COP	4.25	4.30	4.16	4.42

The technical specifications of the heat-pipe based GSHP is shown in Table 3.

Table 3 specifications of the heat-pipe based GSHP

Nominal thermal kW rating	3.0	6.0
Performance data - rated heating output at B0/W35 BS EN14511		
Power consumption	0.8kW	1.6kW
Co-efficient of Performance*	4.05	3.84
Brine (primary) based on 0°C in / -4°C out		
Max inlet temperature °C	25	
Min temperature °C (outlet)	-5 (at standard settings)	
Heating water (secondary) based on 30°C in / 35°C out		
Max flow temperature °C	65 (RHI applications 64C)	65 (RHI applications 60C)
Dimensions		
H X W X L (mm)	515 (H) X 480 (W) X 360 (D)	585 (H) X 610 (W) X 595 (D)
Dry weight kg	60	100

Performance (based on Average Climate) at 35°C		
Seasonal COP	3.68	3.45
Seasonal space heating energy efficiency	139%	130%
Performance (based on Average Climate) at 55°C		
Seasonal COP	2.99	2.97
Seasonal space heating energy efficiency	112%	111%

Window heat recovery systems are heat exchangers attached to building windows frame to permit heat exchange between exhausted and supplied air during the process of building ventilation, including natural ventilation. An example of integrating the window heat recovery system in the building is presented in Figure 18. Heat pipes have two main parts, the cold side (condenser) and the hot side (evaporator), where heat is transferred from evaporator to condenser. The window heat recovery system works in all four seasons, for example, in winter, its purpose is to recover heat from exhausted air to the supplied fresh air, and in summer, the exhausted air cools the supplied air. The specific configuration of the window heat recovery system is shown in Figure 19.

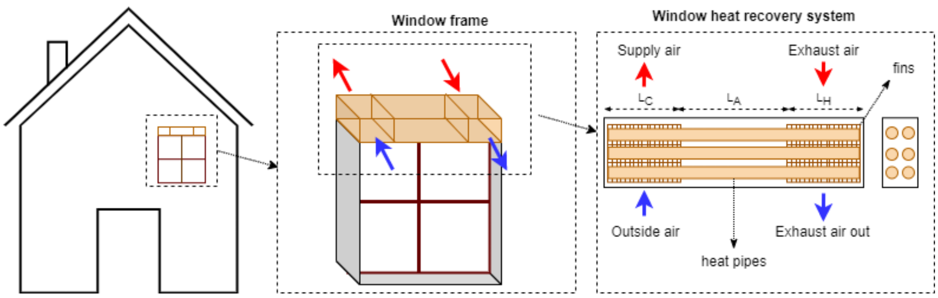


Figure 18 Window heat recovery system integrated with building (Winter example)

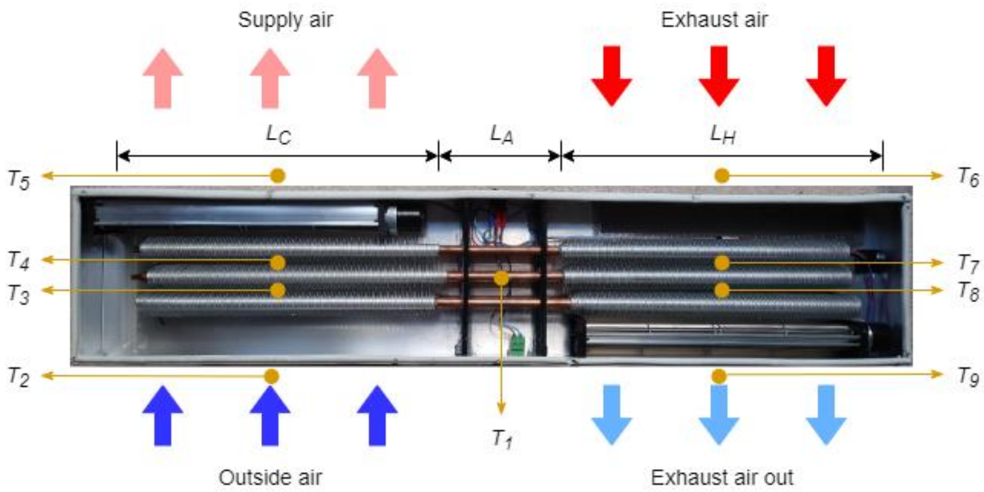


Figure 19 Configuration of the window heat recovery

Numerical simulation results indicate that the thermal effectiveness slightly drops with the rise of the maximum temperature differences between the cold outside air and hot exhaust air, as shown in Figure 20. Temperature differences from 10 °C, 20 °C to 30 °C are investigated with the ventilation rates raised between 10 and 60 m^3/h. It is figured out that the thermal effectiveness is similar in the range of 94.5% and 95.7% when a low ventilation rate of 10 m^3/h. However, the thermal effectiveness decreases between 69.5% and 77.3% when the ventilation rate rises to 60 m^3/h. Thus, the thermal effectiveness declining rates are calculated as 0.06%/°C, 0.14%/°C, 0.22%/°C, 0.285%/°C, 0.345%/°C and 0.39%/°C with varied ventilation rates of 10 m^3/h, 20 m^3/h, 30 m^3/h, 40 m^3/h, 50 m^3/h and 60 m^3/h, respectively. Meanwhile, it is also figured out that the ventilation rates have the most significant impact on the improvement of thermal effectiveness, which reveals that the heat transfer coefficient has noticeable degradation with the rise of the ventilation rate from 10 m^3/h to 60 m^3/h. The thermal effectiveness is dropped by 18.4%, 22.4% and 25.0% with the rise of ventilation rate of 50 m^3/h when the temperature differences are 10 °C, 20 °C and 30 °C, respectively.

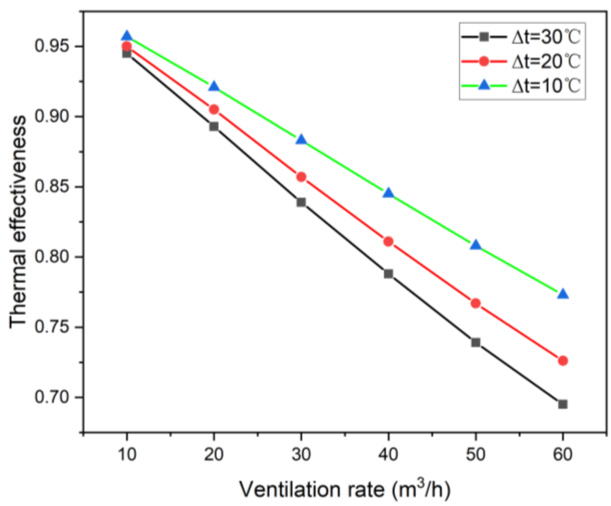


Figure 20 Impact of maximum temperature difference on the thermal effectiveness with ventilation rate varied between 10 to 60 m^3/h

It is figured out that the increase of heat pipe numbers has a significant impact on the improvement of thermal effectiveness, as shown in Figure 21, which reveals that the heat transfer coefficient has a noticeable upgrade when the heat pipe layers increase from $N_p = 2$ to $N_p = 3$, with total heat numbers increasing from 6 to 9. Results indicate that the thermal effectiveness is upgraded from 94.5% to 97.0% when a low ventilation rate of 10 m^3/h. However, the thermal effectiveness decreased between 69.5% and 83.9% when the ventilation rate rises to 60 m^3/h. Thus, the thermal effectiveness decreasing rates are calculated as 1.25%/layer, 2.6%/layer, 4.05%/layer, 5.25%/layer, 6.35%/layer and 7.2%/layer with varied ventilation rates of 10 m^3/h, 20 m^3/h, 30 m^3/h, 40 m^3/h, 50 m^3/h and 60 m^3/h, respectively.

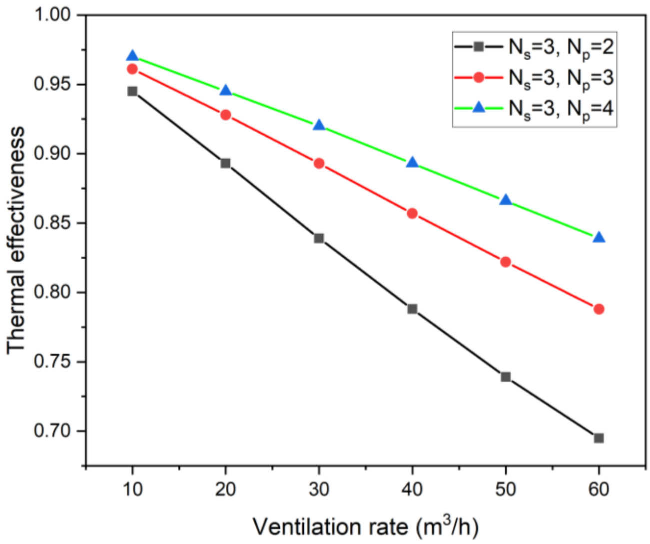


Figure 21. Impact of heat pipe numbers on the thermal effectiveness with ventilation rate varied between 10 to 60 m^3/h

The Dew-point evaporative cooler provides an energy-efficient cooling alternative into the whole building with an extremely compact design where reverse cycle was previously the only option. It provides a more compact option, opening up new installation opportunities where plant room or roof space is restricted. The specific technical information is shown in

Table 4 Specific technical information of the dew-point evaporative cooler.

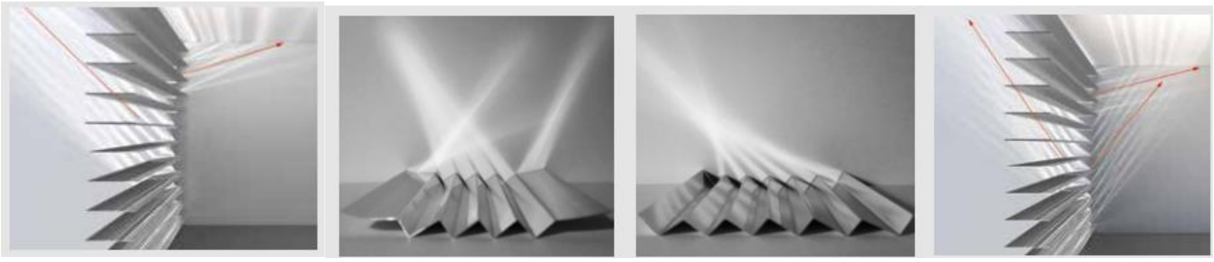
Table 4 Specific technical information of the dew-point evaporative cooler

Location	Design condition	CW3 Leaving Air Temp (°C)	Stand Alone Cooling Capacity (kW)	COP
Arid	42°C DB / 21°C WB	19.5	10	6.8
Temperate	37°C DB / 19°C WB	17.8	14	8.4
Continental	31°C DB / 20°C WB	19.7	12	7.2
Sub-Tropical	31°C DB / 23°C WB	23.0	7	4.3

Natural daylight is extremely valuable for the human physiology. Unfortunately, most office buildings around the world are supplying only 500lx which must be considered as biological darkness with negative consequences for human health and energy waste for artificial lighting. As specialist for daylight systems Dr.-Ing. Helmut Köster developed the optical mirror systems for our daylight blinds to solve the problems of overheating of buildings but still, simultaneously supplying sufficient light to significantly improve the daylight autonomy of offices together with a higher transparency and view through.

Daylight redirection allows to effectively illuminate interiors at greater depths using mirrors or prisms and/or to protect interiors from overheating by redirecting sunlight back into the sky, as shown in Figure 22.

Even white louvers can be provided with a high reflectivity. However, a white louver reflects diffusely, i.e. the light is scattered randomly and evenly. Part of the reflected light is directed inwards, part outwards and a large portion is directed to the underside of the upper louver where it either causes glare to the interior user due to high brightness or - if the underside is darker in color - the light is being absorbed and thus converted into heat. The interior heats up. Which are the improvements by retro technology? Retro technology uses mirror surfaces shaped with high precision and following the laws of mirror optics (angle of incidence = angle of reflection). By means of a special louver contour, the sun is either directed back into the sky and/or towards the interior ceiling and into the room depth. This enables an exact determination of the g-values, the light transmission values the view through and the daylight autonomy in the interior! A white, closed blind directs the energy to outside also! Right! But the view through is prevented if the curtain is closed and the interior is darkened. The lights are switched on even though the sun is shining outside. What a counterproductive building technique.



(a) (b) (c) (d)

Figure 22 Daylighting and reflection

a: Strategic light redirection during high sun in summer: protection against overheating, daylight illumination.

b: Bifocal light redirecting louver to protect against overheating and for a targeted room depth illumination with zenith light.

c: Monofocal light deflecting louver by Fresnel optics, external focal point. Sun protection with horizontal louver position.

d: Light redirection during low sun irradiation in winter: Optimised view, glare-free workplace.

The louver contour forms a Fresnel mirror similar to a fragmented parabola. The Fresnell reflector has its focal point to outside! The light is redirected without closing the louvers. Therefore, the diffuse daylight can transmit through the open louvers and they still protect from direct sun. A darkening of the interior is avoided. The user has a perfect view to outside and the optical communication with the building environment through the open blinds is optimally secured. But once the sun has transmitted to inside, sunlight is short-wave radiation without long-wave heat components in the radiation spectrum. Space has -275°C. A heating happens only by energy conversion of short-wave radiation into long-wave radiation, i.e. by absorption. The intelligence of daylight redirection systems is to reflect the sun back into the sky without absorbing the solar radiation. This is achieved through mirrors by the very specific louver geometries with mirror-like surfaces, which ensures that the sun is reflected back outwards with a single reflection without energy transformation in heat. This primarily depends on the external glazing and the position of the louvers, e.g. in a closed cavity of insulating glass and a surface reflection of 96% of the louvers, gtot-values between 0.05 and 0.07 can be achieved even without a solar protection layer on the outer glazing. If the blinds are installed interior behind a colour-neutral solar protection glass e.g. type 66/32, g values of 0.1 can be realized with open blinds and during high summer sun. The precision of the optical mirrors delivers precise results are shown in Figure 23.

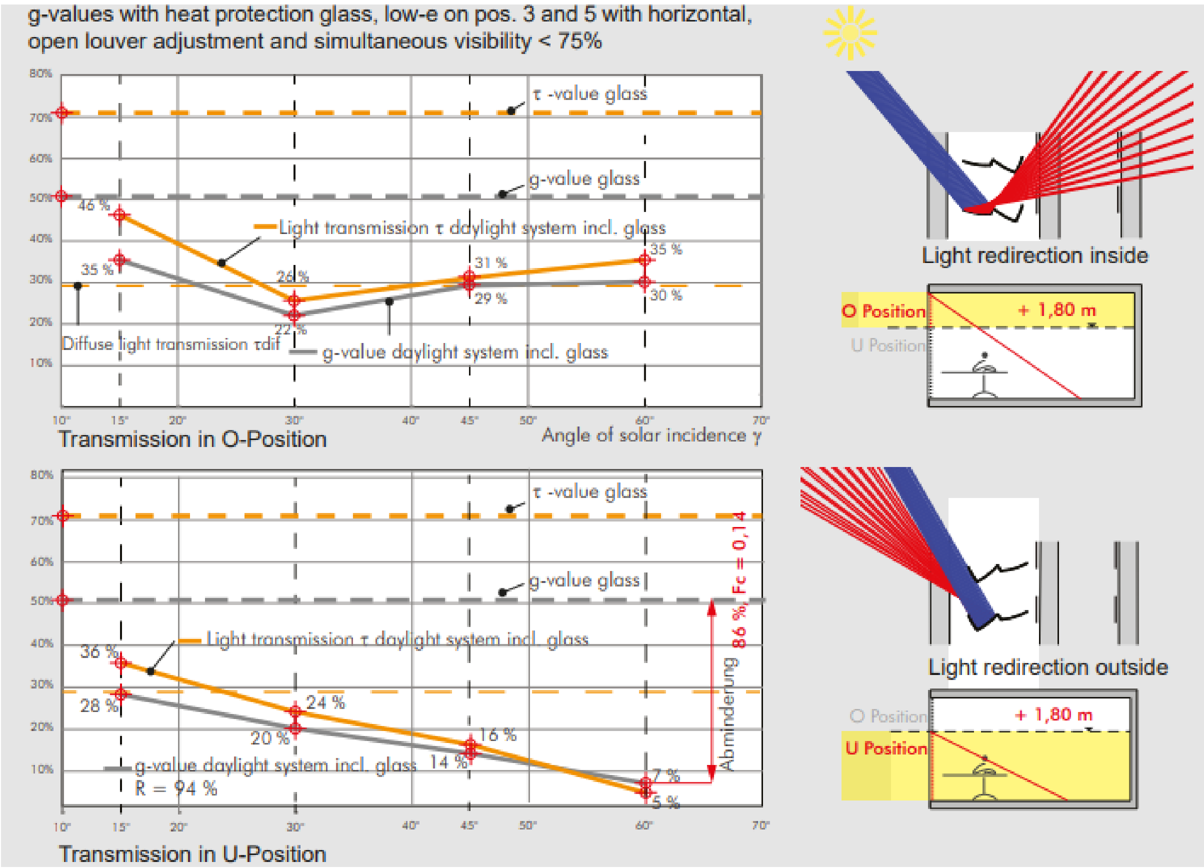


Figure 23 The precision of the optical mirrors delivers precise results

Finally, regarding to the renewable technology, the PV/T technology is proposed with specification shown in Table 5.

Table 5 Specification of the PV/T panel

PV types	mono-crystalline, multi-crystalline, polycrystalline
Thermal collector types	flat-plate collector, evacuated tube collectors
Combined PVT collector	A PVT collector is a combined collector from a PV module for the generation of electrical energy with a highly efficient solar flat collector for the production of heat energy
Module Nominal Efficiency (STC)	Solar to electricity conversion efficiency: 20% (315 W per unit) ; Solar to thermal conversion efficiency: 47% (855 W)
Temperature coefficient for module efficiency	-0.5%/°C
Nominal cell temperature (STC)	45°C
degradation factor	90% < 10 years, 80% <20 years

Life span	> 20 years
Cost	Product cost: €350/pvt, accessory cost: €300/pvt (inverter, cable, assembly tool set, piping, boiler, circulation pump etc.), installation fees: €70/hour (including installation time and labour cost, excluding travel expense), maintenance cost: €70/hour (excluding travel expense),
Dimension	1670*995*60mm, surface area of 1.66m²
Number of cells	number of 60, with each cell dimension of: 156*156mm
System working temperature	Ideal for maximum yield and best benefit, it is recommended to keep the maximum panel temperatures below 55 °C and higher than -15°C

3.2 Economic performance of all retrofit technologies

The cost of each retrofit technologies is composed of manufacture cost, auxiliary cost, installation cost, maintenance cost, as summarized in Table 6. Besides, the life span are also considered.

Table 6 economic performance of each retrofit technology

	Manufacture cost	Auxiliary cost	Installation cost	Maintenance cost	Life span
Insulating breathable membrane	€6.0 /m²	€0.37/m²	€14/m²	0	30
Bio-aerogel panel	€46.5/m² (10mm thick)	€20.9/m² (10mm)	€17.6-58.5/m²	0	30
Silica aerogel panel	15.9 €/m² (10mm)	€20.9/m² (10mm)	€17.6-58.5/m²	0	25
PCM panel	50 euro/m²	0	€6-35/m²	0	20
PV vacuum glazing windows	€421/m²	0	€22.6/m²	0	20
PV/T panels	€421/unit	€300/unit	€140/PVT	2% of investment / year	20

Window heat recovery	€360 per unit	€9/unit	€459 per unit	0	15
Dew-point cooler	£720-1436 per unit	0	£60 per unit cooler	£50 per year per unit cooler	15
Solar assisted heat pump	1 panel - 2.8 kW: 1323 2 panels - 5 KW: 1701 3 panels - 7 kW: 2205 4 panels - 11kW: £2950	€250 per unit	€750 per unit heat pump,	€180 per year	15
Ground source heat pump	1050 €/kW + 15000 €	0	75% of the total	0.5% of investment per year	25

4 Building pilots

4.1 Finish pilot

The prefabricated apartment building (Figure 24) is ready for testing sustainable building technologies in a real environment with real Finnish outdoor climate and real behaviour of inhabitants. The building is located in the city of Helsinki. It was built in 1969 using concrete elements with standard insulation but modernized high efficiency windows. The floor area is 3900 m^2. The building is heated with a municipal district heating system. The primary energy consumption of the building is 200 kWh/m^2, giving it an energy efficiency class F (on a scale from A to G). The district heating system can be partly or completely replaced using exhaust air or ground-source heat pumps, as is the current trend in Finland. The house has mechanical exhaust ventilation with no heat recovery. This could be complemented with heat pumps or replaced with a balanced mechanical exhaust ventilation system for better thermal comfort.

Figure 24 Finnish apartment blocks

For the existing apartment blocks, the prefabricated insulated wall, balcony, roof and window have U-value of 0.47, 0.78, 0.47 and 1.0 W/m^2K. The infiltration rate is 3ACH under 50 pascal pressure difference. Mechanical exhaust fans are used as the ventilation type.

4.2 Greek pilot

This small apartment building was built in 1981 and located in the city of Peristeri, Attica. The orientation of the two main facades is north-south (Figure 25). The building is attached with two other buildings on the east and west sides. The building is approximately 8m long and 15m wide. It accommodates two small spaces on the ground floor of 45m^2 and 25m^2 that used to be shops, one family apartment (4 persons) of approximately 100m^2 on the first floor and another apartment (2 persons) of approximately 100m^2 on the second floor. Each apartment has a living room, three bedrooms, kitchen and bathroom. The building is constructed with concrete pillars and the walls are made of bricks of six hollows and dimensions of 19x9x6cm, using an installation of single brick - polystyrene layer - single brick that offers thermal insulation. The roof has 8cm coating of cement mortar for waterproofing that also offers a kind of thermal insulation. The north and south facades of each floor are equals, approximately 8m long and around 3m high. The building has single glazed aluminium frame windows. These sliding sash windows are of 8mm single glass. Apart from the sliding sash external blinds, each of the two floors has also awnings attached to exterior wall of the building. Heating is supplied through diesel boiler and there is a cooling system provided by air conditioners: one in the one space on the ground floor, three in the first floor (8btu, 8btu and 24btu) and the same in the apartment of the second floor. Hot water is supplied by low pressure water system from a triple-energy boiler that is flexible to work also with a solar collector and electricity.

Figure 25 Greece small apartment building

The existing small apartment has insulated external wall with U-value of 0.96 W/m^2K, and uninsulated ceiling of 3.6 W/m^2K. Besides, single glazing window has poor insulation of 5.9 W/m^2K. Poor airtightness is found with 6.7ACH under 50 pascal pressure difference.

4.3 Portuguese pilot

The building shown in Figure 26 was constructed in 1970 and has two floors with a total area of 130 m^2. It is located in Carvoeira (Mafra Municipality). The façade was built with stone and two layers of plaster. The windows are single glazed with a wood frame. Due to the poor insulation the house has a number of water infiltrations and damp or high humidity. The house is naturally ventilated but the ventilation design was clearly not adequate for good air quality. The house is heated with a 2 kW electric radiator in winter.

Figure 26 Portuguese social house

The social house has poor insulation of external wall, roof and windows with U-value of 2.4W/m^{2}K, 3.8W/m^{2}K and 5.1W/m^{2}K, respectively. Besides, poor airtightness is found with 6.7ACH under 50 pascal pressure difference.

4.4 Spanish pilot

These mill houses are located in San Pedro Regalado neighborhood in Valladolid (Spain) as shown in Figure 27. The houses were constructed in the 50s of last century and are based on the use of walls and load-bearing partitions, on which rest some vaults made of simple hollow bricks. Each house consist of a ground floor, first floor, basement and patio at the back of the plot. The plots have approximately from 60 m2. The current state differs slightly between each of the houses, although all of them share the need for reform to adapt their old structures to the requirements of current comfort, isolation, energy efficiency and improvement in CO2 emissions. 3 single homes are considered for renovation 96, 97 and 97 m2 of living area (accounting for a total 290m2 renovation), with a northeast-southwest orientation. Windows vary from single glazed (4mm thick) with aluminium frame to double glazed (4+6+4 thick) with P.V.C frame, depending on each house. There is no thermal insulation. Heating is supplied mainly through diesel boiler with panel emitters/radiators, and individual electric radiators, depending on the house. There is no cooling system. Hot water is supplied by low pressure water system from the same diesel boiler or from an electric water heater. The U-value is 2 W/m2K for walls and 5.8 W/m2K for single glazed windows, approximately. Energy usage: G (Energy Certification of Existing Buildings).

Figure 27 Spanish mill building

The mill building has no insulation with U-value of 1.69 W/m^{2}K for the wall, 1.64 W/m^{2}K for the roof and 2.8-5.7W/m^{2}K for single- and double- glazing window. Besides, poor airtightness is found with 6.7ACH under 50 pascal pressure difference with natural ventilation.

4.5 British pilot

This 3 beds freehold semi-detached house is located at Nottingham, UK, with the outlook shown in Figure 28. The house has a total 92m^2 which is constructed in 1948, with 3 bedrooms, 2 bathrooms, 2 reception rooms. According to the UK government EPC evaluation, this house is assessed as band D (score:56) and the current primary energy consumption use for only lighting, heating and hot water is estimated as 246 kWh/m^2 per year, with bill estimated for £1034 per year. Moreover, based on this assessment, the house currently produces approximately 5.5 tonnes of carbon emission every year. The floor plan layout is illustrated in Figure 2. The house is built with solid brick external wall without any insulation, with no insulated pitched roof and 100mm insulated loft. The ground floor is all solid with no insulation. All the windows are fully renovated with double glazing in 2012. The house uses boilers and radiators as the main heating system to provide both space heating and hot water, which is powered by natural gas. The room radiators can be controlled with room thermostat and TRVs. And low energy lighting is fixed in each room. The NG8 district is mainly owned by local people of Nottingham with three quarters of houses are owned by the owners, and only one quarter of houses are privately or socially rented houses.

Figure 28 British semi-detached building

The building façade U-value performance is measured from December 2020 to January 2021. Due to the degradation of the building façade over more than 70 years, the U-value of the south/north external wall is 2.1 W/m^{2}K, with west external wall of 2.0 W/m^{2}K. Besides, the U-value of the double-glazing window is 2.4 W/m^{2}K. The U-value of the attic floor and roof are 0.89 W/m^{2}K and 0.22 W/m^{2}K. Moreover, it is found the airtightness is poor with main building and attic space separately conducted by implementing the Pulse airtightness test according to the method A of the BS EN 9972-2015, which has air change rate of 0.67ACH (4Pa pressure difference) and 16.7ACH (50Pa pressure difference) respectively.

5 Final decisions and comprehensive performance

5.1 Final decisions of five building pilots

Table 7 Final decisions of five buildings pilots

SUREFIT Technologies	Finland	Greece	Portugal	Spain	UK
PVT		X		X5	
Bio Aerogel Insulation panel					X
PV Vacuum glazing		X	X	X	X
PV systems			X4		X4
Breathable Membrane		X		X	
PCM panel				X7	
Evaporative coolers					X
Window heat recovery			X	X	X
Solar Assisted Heat Pump (SAHP)			X6		X
Daylight louvers	X		X	X	
Smart Controls		X	X	X	X
Ground Source Heat Pump (GSHP)					X
Prefabricated panel		X3		X3	
Non-SUREFIT Technologies (provided by SUREFIT partner)					
Air vapour barrier	X2				
Other technologies (provided by non-SUREFIT partners)					
PV systems	X1				
Smart Controls					
Ground Source Heat Pump (GSHP)					
Prefabricated module for ducts and pipes	X1				
Prefabricated ventilation container module	X1				

1- Finland will use commercial products (provided by non-SUREFIT partners) in the renovation of the pilot building, including: Ground source HP + Prefabricated model for ducts and pipes+centralized HR unit demand based ventilation+ pipes insulation+ insulation of balcony wall+ insulation roof+ prefabricated ventilation container module+ Two sided PV panels with inverters+ optimized smart controls.
2- Finland raised the possibility of implementation of the innovative Air Vapour barrier provided by project partner WINCO.
3- Considers using Silica Aerogel as insulation.
4 - PV systems assisting Heat Pump compressor .
5- Integration of PVT with existing heating system (gas boiler).
6- Heat Pump providing both DHW and space heating.
7- For a better performance, internal placement will be considered.

5.1.1 Technology selection for the Finnish demo

Table 8 Property of selected technologies for Finnish demo

Selected retrofit technology	Installation area	Parameters
EPS insulation and light gravel	Roof	10 cm + 90 cm
Mineral wool insulation	All balcony walls	15 cm
Winco vapour barrier	One balcony wall	N/A
Pipe insulation	Heat distribution piping	2 cm
Centralized mechanical balanced ventilation with heat recovery	Roof	73% HR efficiency
Daylighting louvers	One apartment: 3 windows and the balcony	10 m^2
Bi-facial PV panels	Roof	140 m^2, 25° tilt
Ground source heat pump	Basement	35 kW heating capacity
Hot water storage tank	Basement	2 m^3

5.1.2 SUREFIT technologies selected for the Greek demo building

Table 9 Property of selected technologies for the Greek demo building

Selected Surefit technologies	Installation area	Parameters
Winco breath membrane	Ceiling of the workshop	2.6cm
Prefabricated panels which integrate together silica aerogel and Winco breath membrane	Southern and northern facades of the 1st apartment floor (external)	Silica: 4cm, membrane: 2.6cm
PV vacuum windows (external shading removed)	South facade	N/A
PV/T panels for the production of electricity, DHW and space heating (space heating will be supplemented by the existing oil boiler)	Roof	6 panels (PowerTherm), each panel size: 1.67m*1.005m
Smart controls		

Selected retrofit technologies	Installation area	Parameters
PVC windows of double glazing with low E coating and of 12mm air gap between the panes	North facade	U-value: 1.9 W/m2K, g_w: 0.48
PVC windows of double glazing with low E coating and of 12mm air gap between the panes	Kitchen, bathroom	U-value: 2.2 W/m2K, g_w: 0.48

5.1.3 SUREFIT technologies selected for the Portuguese demo building

Table 10 Property of selected technologies for the Portuguese demo building

Selected retrofit technologies	Installation area	Parameters
PV vacuum window	South facade	N/A
PV panels	Roof	3 panels, 1200W
Silica aerogel insulation panel	All the external wall and roof (inside)	2cm
Window heat recovery	West window (also replaced by aluminum double glazing)	One room unit
SAHP	The exterior unit will be placed in the east façade and the thermodynamic panel on the roof.	5kW Provide both DHW and space heating
Fan coil units	The first floor has 3 units (kitchen, living room and bedroom). The second floor has 2 units.	supply: 35°C, return: 30°C

5.1.4 SUREFIT technologies selected for the Spanish demo building

Table 11 Property of selected technologies for the Spanish demo building

Selected retrofit technology	Installation area	Parameters
Silica-aerogel insulation (pre-fabricated panel)	External walls of 2 apartments	2 cm
Insulating breather membrane (pre-fabricated panel	External walls of 2 apartments	2.6 cm
Insulating breather membrane	Roof	2.6 cm
PCM	Ceiling of one bedroom	3.2 cm
PV vacuum windows	All windows, except basement windows	17.4 m^2
Daylighting louvers	All windows, except basement windows	17.4 m^2
Window heat recovery	1 bedroom and 1 living room in each apartment	6 units
PV/T system	Roof	10 m2, 50° tilt
Hot water storage tank	Patio?	1 m^3

5.1.5 SUREFIT technologies selected for the British demo building

Table 12 Properties of selected technologies for the British demo building

Selected retrofit technology	Installation area	Parameters
Bio-aerogel insulation panels	West party wall (internal)	2cm
Silica-aerogel insulation panels	East and south external wall (internal)	2cm
PV vacuum windows	South facade	N/A
Window heat recovery	2 Bedrooms and 1 living room	Three room units
PV panels (Surefit?)	South to west roof	Peak power 3.6kW
Solar assisted heat pump	Panels placed on the south façade	2.8kW heating capacity Primarily for hot water
Ground source heat pump	Borehole installation in the garden	4kW heating capacity Primarily for space heating
Hot water storage tank	Garden	800L Connected with SAHP and GSHP

5.2 Energy performance prediction

5.2.1 Energy performance before and after retrofit for Finnish pilot

Table 13 Energy performance for per- and post-retrofit stage for Finnish pilot

Renovation measure	Pre-retrofit	Post-retrofit
U-value, walls (W/m2K)	0.47	0.47
U-value, balcony (W/m2K)	0.78	0.22
U-value, roof (W/m2K)	0.47	0.09
U-value, windows (W/m2K)	1	1
Infiltration (n50, ACH)	3	1.5
Ventilation type	Mechanical exhaust	Mechanical balanced
Ventilation HR eff (%)	0	73
Solar thermal (m2)	0	0
PV panels (m2)	0	140
GSHP capacity (kW_{th})	0	35
Hot water tank (m^3)	0	2
Heat distribution eff. (%)	80	90
Hot water loss (W/m2)	2.5	1.75

In the Finnish pilot, the total district heating demand has decreased from 133.6 kWh/m^2 to 31.7 kWh/m^2 for pre-and post-retrofit stages. In addition, the total electricity demand increases from 30.0 kWh/m^2 to 33.7 kWh/m^2, as shown in Table 13. The total purchased energy demand diminishes from 163.6 kWh/m^2 to 65.4 kWh/m^2 whereas the primary energy declines from 102.8 kWh/m^2 to 56.3 kWh/m^2 for pre-and post-retrofit stages. Meanwhile, the CO_2 emission has decreased from 32.3 kg/m^2 to 10.2 kg/m^2, as shown in Table 14.

Table 14 Energy consumption for pre- and post-retrofit stages for Finnish pilot

	Pre-retrofit (kWh/m^2.year)	Post-retrofit (kWh/m^2.year)
District heating total	133.6	31.7

SH + vent	89.2	16.4
DHW	42.6	15.3
Electricity total	30.0	33.7
Equip + Light, tenant	18.9	19.4
Equip + Light, facility	3.9	3.4
HVAC aux	5.0	3.8
Heat pump	0.0	9.1
Sauna	2.1	1.8

Table 15 Energy reductions for the Finnish pilot

	Pre-retrofit	Post-retrofit
Purchased energy (kWh/m²)	163.6	65.4
Reduction (%)	0 %	-60.0 %
Primary energy (kWh/m²)	102.8	56.3
Reduction (%)	0 %	-45.3 %
Emissions (kg/m²)	32.3	10.2
Reduction (%)	0 %	-68.3 %

5.2.2 Energy performance before and after retrofit for Greek pilot

Table 16 Property specifications for pre- and post-retrofit

Property	Pre-retrofit	Post-retrofit (oil backup heating)
U-value, external walls (W/m2K)	0.96	0.22
U-value, windows (W/m2K)	5.9	0.6/1.9/2.2

Area, Vacuum glazing window (m2)	0	5.62
Infiltration (ACH, n50)	6.7	0.07
PV-T panels (m2)	0	10.07
Hot water tank (m3)	0.4	0.8

Table 17 illustrates the purchased energy use of the Greek pilot for both pre-and post-retrofit stages. In addition, the total purchased energy demand diminishes from 120.9 kWh/m^2 to 44.9 kWh/m^2 with a 63% of reduction rate whereas the primary energy declines from 143.5 kWh/m^2 to 53.9 kWh/m^2 with a 62% of reduction rate for pre-and post-retrofit stages. Meanwhile, the CO2 emission has decreased from 36.6 kg/m^2 to 13.9 kg/m^2.

Table 17 Energy performance for pre- and post-retrofit stages for the Greek pilot

Purchased energy use (kWh/m2/year)		
	Pre-retrofit	Post-retrofit (oil backup heating)
Oil heating total	105.6	38.3
Space heating & DHW	105.6	38.3
Electricity total	15.3	6.6
Equip + Light	10.4	4.2
HVAC aux	0.3	0
Space cooling	4.6	2.4
Solar energy total		24.4
PV self-consumption		8.5
PV sold		15.9
PV self-consumption rate		35%

	Pre-retrofit	Post-retrofit (oil backup heating)
Purchased energy (kWh/m2)	120.9	44.9
Reduction (%)	-	63%
Primary energy (kWh/m2)	143.5	53.9
Reduction (%)	-	62%
CO2 Emissions (kg/m2)	36.6	13.9
Reduction (%)	-	62%

5.2.3 Energy performance before and after retrofit for Portuguese pilot

Table 18 indicates the specific value of all the properties during pre-and post-retrofit stages in the Portuguese pilot.

Table 18 Property specifications for pre- and post-retrofit stages in the Portuguese pilot

Property	Pre-retrofit (intermittent heating)	Post-retrofit
U-value, external walls (W/m2K)	2.40	0.57
U-value, roof (W/m2K)	3.80	0.63
U-value, windows (W/m2K)	5.1	0.6/5.1
Area, PV vacuum window (m2)	0	1
Infiltration (ACH, n50)	6.7	6.7
Window HR efficiency (%)	0	0.76
Solar thermal collector (m2)	0	5.1
PV panels (m2)	0	7.47

SAHP capacity (kW)	0	5
Hot water tank (m3)	0	0.32
Dimensioning heating power (kW)	11.2	3.6

Table 19 illustrates the purchased energy use of the Portuguese pilot for both pre-and post-retrofit stages. In addition, the total purchased energy demand diminishes from 115.4 kWh/m^2 to 18.1 kWh/m^2 with an 84% of reduction rate whereas the primary energy declines from 163.0 kWh/m^2 to 27.0 kWh/m^2 with an 83% of reduction rate for pre-and post-retrofit stages. Meanwhile, the CO2 emission has decreased from 28.3 kg/m^2 to 4.6 kg/m^2.

Table 19 Energy performance for pre- and post-retrofit stages in the Portuguese pilot

Purchased energy use (kWh/m2/year)		
	Pre-retrofit **(intermittent heating)**	Post-retrofit
Oil heating total	18.3	0
DHW	18.3	0
Electricity total	97.1	18.1
Equip + Light	13.2	6
HVAC aux	0	1.4
Electric radiators	83.9	0
Heat pump	0	10.7
Solar energy total		23.9
PV self-consumption		10
PV sold		13.9
PV self-consumption rate		42%
Purchased energy (kWh/m2)	115.4	18.1
Reduction (%)	-	84%

Primary energy (kWh/m2)	163.0	27.0
Reduction (%)	-	83%
CO2 Emissions (kg/m2)	28.3	4.6
Reduction (%)	-	84%

5.2.4 Energy performance before and after retrofit for Spanish pilot

Table 20 indicates the specifications of different renovation measures for the Spanish pilot for pre-and post-retrofit scenarios.

Table 20 Specifications of renovation measures for ore- and post-retrofit stages in the Spanish pilot

Renovation measure	Pre-retrofit	Post-retrofit
Wall insulation thickness (cm)	0	2
Roof insulation thickness (cm)	0	0
Membrane thickness (cm)	0	2.6
U-value, walls (W/m2K)	1.69	0.39 / 1.69
Insulated wall area (m2)	0	147
U-value, roof (W/m2K)	1.64	0.66
U-value, windows (W/m2K)	2.8 / 5.7	0.6
PV glazing area (m2)	0	17.4
PCM (cm)	0	3.2
Infiltration (n50, ACH)	6.7	0.11
Ventilation type	Natural	Mech. Balanced
Ventilation HR (%)	0	75
ST roof (m2)	0	10

PV roof (m2)	0	10
Hot water tank (m3)	0	1
Daylighting louvers (m2)	0	17.4

In the Spanish pilot, the total fuel demand has decreased from 109.5 kWh/m^2 to 56.4 kWh/m^2 for pre-and post-retrofit stages. In addition, the total electricity demand decreases from 19.4 kWh/m^2 to 13.1 kWh/m^2, as indicated in Table 21. The total purchased energy demand diminishes from 134.0 kWh/m^2 to 69.5 kWh/m^2 whereas the primary energy declines from 146.5 kWh/m^2 to 80.1 kWh/m^2 for pre-and post-retrofit stages. Meanwhile, the CO_2 emission has decreased from 25.5 kg/m^2 to 13.7 kg/m^2, as shown in Table 22.

Table 21 Energy performance of the Spanish pilot

Energy type	Pre-retrofit	Post-retrofit
Fuel tot	109.5	56.4
SH	93.2	
DHW	16.2	
Elec tot	19.4	13.1
Equip + Light	19.2	
HVAC aux	0.2	
Electric heating	0.0	

Table 22 Energy consumption for pre- and post-retrofit stages in the Spanish pilot

	Pre-retrofit	Post-retrofit
Purchased energy (kWh/m^2)	134	69.5
Reduction (%)		48.3 %
Primary energy (kWh/m^2)	146.5	80.1
Reduction (%)		45.3 %
Emissions (kg-CO_2/m^2)	25.5	13.7
Reduction (%)		46.2 %

5.2.5 Energy performance before and after retrofit for British pilot

Table 23 indicates the specific value of all the properties during pre-and post-retrofit stages in the British pilot.

Table 23 Property specifications for pre- and post-retrofit stages in the British pilot

Property	Pre-retrofit	Post-retrofit
U-value, external walls (W/m2K)	2.09	0.55/2.09
U-value, roof (W/m2K)	0.22	0.22
U-value, windows (W/m2K)	2.4/2.5	0.6/2.4/2.5
Area, Vacuum glazing window (m2)	0	13.4
PCM (cm)	0	0
Infiltration (ACH, n50)	16.1	16.1
Window HR efficiency (%)	0	0.76
Solar thermal collector (m2)	0	3.4
SAHP capacity (kW)	0	2.8
PV panels (m2)	0	18.68
GSHP capacity (kW)	0	4
Hot water tank (m3)	0	0.8

In the British pilot, the total gas heating demand has decreased from 109.5 kWh/m^2 to 0 for pre- and post-retrofit stages. In addition, the total electricity demand increases from 24.5 kWh/m^2 to 60.8 kWh/m^2. The total purchased energy demand diminishes from 206.8 kWh/m2 to 60.8 kWh/m^2 whereas the primary energy declines from 242.7 kWh/m^2 to 91.2 kWh/m^2 for pre-and post-retrofit stages. Meanwhile, the CO2 emission has decreased from 42.7 kg/m^2 to 14.0 kg/m^2, as shown in Table 24.

Table 24 Energy performance for pre- and post-retrofit stages in the British pilot

Purchased energy use (kWh/m2/year)		
	Pre-retrofit	Post-retrofit
Gas heating total	182.3	0

Space heating	182.3	0
Electricity total	24.5	60.8
Equip + Light	8.6	7.7
HVAC aux	0.2	0.8
Space heating (dinning room)	7.4	6
DHW	8.3	0
SAHP	0	23.3
GSHP	0	23
Solar energy total		2.9
PV self-consumption		2.8
PV sold		0.1
PV self-consumption rate		97%
	Original	Final combination
Purchased energy (kWh/m2)	206.8	60.8
Reduction (%)	-	71%
Primary energy (kWh/m2)	242.7	91.2
Reduction (%)	-	62%
CO2 Emissions (kg/m2)	42.7	14.0
Reduction (%)	-	67%

5.3 Thermal comfort analysis

5.3.1 Thermal comfort before and after retrofit for Finnish pilot

In the Finnish pilot, the daytime indoor temperature does not exceed 21°C during both pre-and post-retrofit stages. The hourly rate when the indoor temperature is greater than 25°C has diminished from 11.9% to 0.1% for pre-and post-retrofit stages. The maximum temperature decreases from 30.3°C to 25.2°C. Both pre-and post-retrofit stages have the hourly CO_2 concentration being less than 1800ppm scenarios, as indicated in Table 25.

Table 25 Thermal comfort for pre- and post-retrofit stages in the Finnish pilot

Indoor conditions	Pre-retrofit	Post-retrofit
T<21 °C	0.0 %	0.0 %
T>25 °C	11.9 %	0.1 %
T_{max}	30.3 °C	25.2 °C
CO_2 < 1200 ppm	100 %	100 %
CO_2 < 1800 ppm	100 %	100 %

5.3.2 Thermal comfort before and after retrofit for Greek pilot

In the Greek pilot, the daily mean indoor air temperature does not exceed 21°C during both pre- and post-retrofit stages with the hourly rate decreasing from 22.9% to 6.4%. The hourly rate when the indoor temperature is greater than 25°C has increased from 7.1% to 16.0% for pre-and post-retrofit stages. The maximum temperature increases from 28.7°C to 30.0°C. For CO_2 concentration less than 1200 ppm, the hourly rate decreases from 26.3% to 7.0%, whereas from 83.3% to 46.6% for that of less than 1800 ppm during pre-and post-retrofit, as shown in Table 26.

Table 26 Thermal comfort for pre- and post-retrofit stages in the Greek pilot

	Pre-retrofit	Post-retrofit (oil backup heating)
Indoor conditions		
Proportion of time, T<21 degC (%)	22.9	6.4
Proportion of time, T>25 degC (%)	7.1	16.0
T_max (degC)	28.7	30.0

Proportion of time, CO2 < 1200 ppm (%)	26.3	7.0
Proportion of time, CO2 < 1800 ppm (%)	83.3	46.6

5.3.3 Thermal comfort before and after retrofit for Portuguese pilot

In the Portuguese pilot, the indoor temperature does not exceed 21°C during both pre-and post-retrofit stages with the hourly rate increasing from 49.0% to 52.9%. The hourly rate when the indoor temperature is greater than 25°C has decreased from 7.1% to 3.6% for pre- and post-retrofit stages. The maximum temperature decreases from 27.9°C to 27.1°C. For CO_2 concentration less than 1200 ppm, the hourly rate increases from 34.2% to 100.0%, whereas from 72.5% to 100% for that of less than 1800 ppm during pre-and post-retrofit, as indicated in Table 27.

Table 27 Thermal comfort for pre- and post-retrofit stages in the Portuguese pilot

	Pre-retrofit **(intermittent heating)**	Post-retrofit
Indoor conditions		
Proportion of time, T<21degC (%)	49.0	52.9
Proportion of time, T>25 degC (%)	7.1	3.6
T_max (degC)	27.9	27.1
Proportion of time, CO2 < 1200 ppm (%)	34.2	100.0
Proportion of time, CO2 < 1800 ppm (%)	72.5	100.0

5.3.4 Thermal comfort before and after retrofit for Spanish pilot

In the Spanish pilot, the hourly rate when the indoor temperature is less than 18 °C is 5.1% for the pre-retrofit scenario whereas the post-retrofit does not have this scenario. The hourly rate when the indoor temperature is greater than 25°C has decreased from 11.9% to 4.1% for pre-and post-retrofit stages. The maximum temperature decreases from 30.5°C to 27.9°C. For CO_2 concentration less than 1200 ppm, the hourly rate increases from 41.3% to 100.0%, whereas from 98.1% to 100% for that of less than 1800 ppm during pre-and post-retrofit, as shown in Table 28.

Table 28 Thermal comfort for pre- and post-retrofit stages in the Spanish pilot

	Pre-retrofit	Post-retrofit
Indoor conditions		
T < 18 °C	5.1 %	0.0 %
T > 25 °C	11.9 %	4.1 %
T_{max}	30.5 °C	27.9 °C
CO_2 < 1200 ppm	41.3 %	100 %
CO_2 < 1800 ppm	98.1 %	100 %

5.3.5 Thermal comfort before and after retrofit for a British pilot

In the British pilot, the indoor temperature does not exceed 20°C during both pre-and post-retrofit stages. The hourly rate when the indoor temperature is greater than 25°C has decreased from 0.4% to 0.2% for pre-and post-retrofit stages. The maximum temperature decreases from 29.1°C to 27.3°C. Both pre-and post-retrofit stages have the hourly CO_2 concentration being less than 1800ppm scenarios in the British pilot, as shown in Table 29.

Table 29 Thermal comfort for pre- and post-retrofit in the British pilot

	Pre-retrofit	Post-retrofit
Indoor conditions		
Proportion of time, T<20 degC (%)	0.0	0.0
Proportion of time, T>25 degC (%)	0.4	0.2
T_max (degC)	29.1	27.3
Proportion of time, CO2 < 1200 ppm (%)	100.0	100.0

Proportion of time, CO_2 < 1800 ppm (%)	100.0	100.0

5.4 Economic performance calculation

5.4.1 Economic performance of Finish pilot

Final Case parameters:

- Commercial EPS Insulation Thickness of 10.0 cm together with 90.0 cm gravel placed on the roof.
- Insulation with mineral wool (15.0 cm thickness) for all balcony walls.
- Breathable membrane incorporated only in one balcony wall.
- Insulation of pipe system with 2.0 cm insulator.
- Heat Recovery by centralized mechanical balanced ventilation located on the roof.
- Daylight louvres for 3 windows and the balcony, covering 10 m^2.
- 84 commercial PV panels are exploited for the 140 m^2
- Commercial GSHP of 35.0 kW capacity

In the post-retrofit scenario of the Finnish pilot, the payback period is 26.28 years with a zero inflation rate whereas 16.64 years with the EU average inflation rate. The payback period of the Finnish pilot with its inflation rate is 18.20 years, as shown in Table 30. Results indicate that the payback period of all three scenarios is beyond 10 years.

Table 30 PBP – Intermittent heating – FINAL case FI

PBP FINAL – Intermittent FI					
			PBP (years) **with Inflation Rate Values**		
Category	**No.**	**Scenario Description**	**PBP** when h_{FI}	**PBP** when h_0	**PBP** when h_{EU}
Final Scenario		Roof Commercial Insulation & balcony com. Insulation & pipe com. Insulation & com. HR & louvers & com. PV & com. GSHP	18.20	26.28	16.64

5.4.2 Economic performance of Greek pilot

The applied retrofit simulation implies only the first-floor apartment and not the overall building as received in the previous simulations. The floor area of the dwelling occupies almost 90 m^2.

- The breathable airtight membrane on the ceiling of the workshop is located on the ground floor (90 m^2).
- Prefabricated panels with silica and breathable membrane on the southern and northern facades (externally – 30.7 m^2). The silica thickness is 4.0 cm.
- PV vacuum windows will be exploited in the south façade.
- PV/T for electricity production, DHW and space heating. The latter will be supplemented by the existing oil boiler). There will be 6 PV/T modules placed on the roof.

- Smart Control System
- Commercial double glazed PVC windows

In the post-retrofit scenario of the Greek pilot, the payback period is 10.28 years with a zero inflation rate whereas 8.11 years with the EU average inflation rate. The payback period of the Greek pilot with its inflation rate is 8.08 years, as shown in Table 31. Results indicate that the payback periods with the Greek and EU average inflation is under 10 years.

Table 31 PBP – Intermittent heating – FINAL case GR

PBP FINAL – Intermittent GR					
			PBP (years) with Inflation Rate Values		
Category	No.	Scenario Description	PBP when h_{GR}	PBP when h_0	PBP when h_{EU}
Final Scenario		Silica-aerogel & Breathable membrane & PV-VG & Commercial Double windows & PV/T	8.08	10.28	8.11

5.4.3 Economic performance of Portuguese pilot

Finally, via the guidance of D2.2. and interpreting the occupants' requirements, the definitive, applied retrofit scenario implies the following:

- The simulation considers the overall building.
- Silica-aerogel insulation panel covering the overall external wall and the roof from the inside. The exploited blanket thickness will be 2cm.
- WHR system will be introduced only in one room; therefore, only one unit will be used.
- PV vacuum windows will be exploited in the south façade and only in 1 m^2 of area.
- PV panels of 1200W capacity (3 panels) are located on the roof.
- SAHP of 5kW together with DHW and space heating.
- Fan Coil units (not within the boundaries of the SUREFIT project)

In the post-retrofit scenario of the Portuguese pilot, the payback period is 12.55 years with a zero inflation rate whereas 9.08 years with the EU average inflation rate. The payback period of the Portuguese pilot with its inflation rate is 10.89 years, as shown in Table 32. Results indicate that the payback period with the EU average inflation is under 10 years.

Table 32 PBP – Intermittent heating – FINAL case PT

PBP FINAL – Intermittent PT					
			PBP (years) with Inflation Rate Values		
Category	No.	Scenario Description	PBP when h_{PT}	PBP when h_0	PBP when h_{EU}
Final Scenario		Silica-aerogel & PV-VG & WHR & SAHP & PV	10.89	12.55	9.08

The current assumption brings an 84% reduction in the purchased energy index, while 83% less primary energy is used compared with the original case.

5.4.4 Economic performance of Spanish pilot

The finalized case of SP simulation scenario assessed, imply the following:

- 2.0 cm of silica aerogel in pre-fabricated panels covering the external wall of the *three* apartments (floor area of 223.7 m^2).
- An insulating breathable membrane was applied as envelope to the external wall and roof of the *three* apartments.
- PCM panels of a bedroom's internal ceiling.
- PV vacuum windows will be exploited everywhere except the basement, covering a total area of 14.4 m^2.
- Daylight louvers in the same area the PV/VG cover.
- Six (6) units of WHR system will be introduced.
- PV/T system panels extending to 10m^2 on the roof.

In the post-retrofit scenario of the Spanish pilot, the payback period is 40.86 years with a zero inflation rate whereas 21.54 years with the EU average inflation rate. The payback period of the Portuguese pilot with its inflation rate is 19.02 years, as shown in Table 33. Results indicate that the payback period of all three scenarios is beyond 10 years.

Table 33 PBP – Intermittent heating – FINAL case SP

PBP FINAL – Intermittent SP					
			PBP (years) **with Inflation Rate Values**		
Category	**No.**	**Scenario Description**	**PBP** when **h_{SP}**	**PBP** when **h_0**	**PBP** when **h_{EU}**
Final Scenario		Silica & Membrane & PCM & PV-VG & Louvers & WHR & PV/T	19.02	40.86	21.54

5.4.5 Economic performance of British pilot

The final "to-be-implemented" scenario, is assessed, where the occupant, the demo-building supervisors and the simulations results indicated the following inputs:

- Bio-aerogel insulation panel covering the west party wall (internally) of 46.9 m^2. The exploited blanket thickness will be 2.0 cm.
- The eastern and southern external walls occupying 58.1 m^2 will be insulated with 2.0 cm thickness silica-aerogel panels.
- PV vacuum windows will be exploited in the south façade only.
- Three units of WHR system will be introduced.
- PV panels of 3.6 kW peak power located on roof.
- SAHP of 2.8 kW primarily for DHW.
- GSHP of 4 kW capacity primarily for space heating purposes.
- A 800 L volume hot water storage tank will be placed in the garden.

In the post-retrofit scenario of the British pilot, the payback period does not exist with a zero inflation scenario since the retrofitted energy mixture is quite expensive. The AaC values achieved are of the magnitude of 200 to 300€ per annum. However, the target of consumption decrease is achieved. Meanwhile, the payback period is 43.22 years with the Greek pilot's inflation whereas 45.28 years with the EU average inflation rate, as shown in Table 34.

Table 34 PBP – Intermittent heating – FINAL case UK

PBP FINAL – Intermittent UK					
			PBP (years) **with Inflation Rate Values**		
Category	**No.**	**Scenario Description**	**PBP** when $\mathbf{h_{UK}}$	**PBP** when $\mathbf{h_0}$	**PBP** when $\mathbf{h_{EU}}$
Final Scenario		Silica & Bio-aerogel & PV-VG & WHR & SAHP & PV & GSHP	43.22	-	45.28

6. Conclusions

In this work package, the results of technology sizing are reported from the perspective of energy, economic and thermal comfort. In the Finnish pilot, the purchased energy reduction rate is 60%, with primary energy reduction rate of 45.3%, and carbon emission reduction rate of 68.3%. The calculated payback period is 16-26 years, with uncomfortable hours reduced from 11.9% to 0.1% and maximum indoor temperature reduced to 25.2℃. In the Greek pilot, the purchased energy reduction rate is 63%, with primary energy reduction rate of 62%, and carbon emission reduction rate of 62%. The calculated payback period is 8-10 years, with uncomfortable hours increased from 7.1% to 16% and maximum indoor temperature increased to 30℃. In the Portugal pilot, the purchased energy reduction rate is 84%, with primary energy reduction rate of 83%, and carbon emission reduction rate of 84%. The calculated payback period is 9-13 years, with uncomfortable hours reduced from 7.1% to 3.6% and maximum indoor temperature reduced to 27.1℃. In the Spanish pilot, the purchased energy reduction rate is 55.6%, with primary energy reduction rate of 52.5%, and carbon emission reduction rate of 53.9%. The calculated payback period is 19-41 years, with uncomfortable hours reduced from 11.9% to 4.1% and maximum indoor temperature reduced to 27.9℃. In the British pilot, the purchased energy reduction rate is 71%, with primary energy reduction rate of 62%, and carbon emission reduction rate of 67%. The calculated payback period is 43-45 years, with uncomfortable hours reduced from 0.4% to 0.2% and maximum indoor temperature reduced to 27.3℃.

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