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Abbreviations

BREEAM	Building Research Establishment Environmental Assessment Method
CO ₂	Carbon dioxide
CO ₂ e	CO ₂ -equivalents
EoL	End of Life
EPS	Expanded polystyrene
EUI	Energy Use Intensity
GHGs	Greenhouse gases
GSHP	Ground source heat pump
GWP	Global warming potential
ISO	International Organization for Standardization
KPI	Key performance indicators
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PCM	Phase change material
PUR	Polyurethane
PV	Photovoltaic
PV/T	Photovoltaics and thermal
SAHP	Solar-assisted heat pump
SEER	Seasonal Energy Efficiency Ratio



Publishable summary

The SUREFIT project, funded by the European Union's Horizon 2020 research and innovation program (grant agreement No. 894511), aims to provide sustainable and affordable solutions for retrofitting existing domestic buildings to significantly reduce energy consumption and carbon emissions. Deliverable D8.2 focuses on the environmental sustainability and social acceptance of a range of innovative retrofit technologies. This report outlines the findings of the Life Cycle Assessment (LCA) and social surveys conducted to evaluate the performance of these technologies compared to conventional systems.

Key retrofit technologies assessed in the report include bio-aerogel insulation panels, photovoltaic (PV) vacuum glazing units, prefabricated insulation panels, phase change material (PCM) panels, solar-assisted heat pumps, ground source heat pumps, evaporative cooling units, and daylight louvers, among others. The LCA methodology applied a cradle-to-grave analysis, assessing the environmental impacts from raw material extraction through manufacturing, installation, operational use, and end-of-life disposal or recycling. The functional unit for comparison was defined as carbon emissions per square meter of building space per year, ensuring consistent and scalable results.

The findings revealed that innovative technologies outperformed conventional systems across all key life cycle stages, with some technologies reducing carbon emissions by over 70%. For instance, the solar-assisted heat pump and evaporative cooling units demonstrated significant carbon savings, particularly during the operational phase, where emissions are typically the highest. Technologies such as bio-aerogel insulation panels and PV vacuum glazing units also showed substantial reductions in heating and cooling demands, directly contributing to lower energy consumption and carbon emissions.

In addition to the environmental assessment, the report analysed the social acceptance of these retrofit technologies through surveys and interviews with building users. The initial and mid-term surveys explored user perceptions regarding the installation process, operational benefits, and overall satisfaction. Results indicate a positive reception of these sustainable technologies, especially when they deliver on cost savings and ease of use. However, there were noted concerns regarding the upfront costs and the potential disruption during installation, which may affect broader market acceptance. The report suggests that addressing these concerns, along with improving public awareness of the long-term environmental and financial benefits, will be key to successful adoption.

Deliverable D8.2 provides valuable insights into the potential of sustainable retrofit technologies to contribute to the decarbonization of the building sector, which is responsible for a significant portion of global carbon emissions. By demonstrating the life cycle carbon savings of these technologies, the report supports policymakers, industry professionals, and building owners in making informed decisions about energy-efficient retrofits. The findings emphasize the importance of integrating innovative technologies into national and international sustainability strategies to meet climate targets, while also considering the practical challenges related to cost, ease of implementation, and user acceptance.



Introduction

Leading Beneficiary: UNOTT

Participants: FSM, AMS, ISQ, AALTO

This deliverable report presents the activities that have been conducted until today in the framework of T8.2 – Environmental sustainability and social acceptance assessment.

Based on the description of T8.2, the following activities should be realised:

- An environmental sustainability assessment by means of Life Cycle Assessment studies. The CO₂ emissions savings of the technologies for heating, cooling or lighting will come from the comparison with conventional systems.
- The social acceptability of the technologies will be performed from the questionnaires and interviews with the public and building users.



1 Introduction to the Life Cycle Analysis

1.1 Background

The building sector is one of the largest contributors to global carbon emissions, accounting for approximately 40% of energy-related carbon dioxide (CO₂) emissions worldwide. This is due to the extensive energy demands of buildings for heating, cooling, lighting, and other operational needs, as well as the significant carbon footprint associated with the construction and maintenance of buildings. As the global population grows and urbanization increases, the energy consumption and associated carbon emissions from the building sector are expected to rise further, exacerbating the challenges of climate change. Reducing carbon emissions in this sector is, therefore, crucial for meeting international climate targets, such as those set out in the Paris Agreement, and for transitioning to a more sustainable and low-carbon future.

1.2 Overview of Retrofitting Existing Buildings

Given the large number of existing buildings worldwide, retrofitting these structures presents a significant opportunity to reduce carbon emissions on a large scale. Building retrofits involve upgrading or replacing outdated systems and components with more energy-efficient and environmentally friendly alternatives. This can include improvements to insulation, heating, cooling, lighting, and the incorporation of renewable energy sources. Retrofitting is particularly important because many existing buildings were constructed before modern energy efficiency standards were implemented, meaning they often have poor energy performance. By retrofitting these buildings, it is possible to achieve substantial reductions in energy consumption and carbon emissions, extending the lifespan of the buildings while reducing their environmental impact. Innovative technologies in building retrofits, such as advanced insulation materials, energy-efficient glazing, and renewable energy systems, offer the potential for even greater carbon savings compared to conventional approaches.

1.3 Objectives of the Study

The primary objective of this study is to assess the life cycle carbon emission savings of innovative building retrofit technologies compared to conventional systems. This assessment will be carried out using Life Cycle Assessment (LCA) methodology, which provides a comprehensive analysis of the environmental impacts associated with the entire life cycle of the technologies, from raw material extraction through to disposal. The study aims to quantify the CO₂ emission savings of innovative technologies used for cooling, heating, and lighting in retrofitted buildings and to determine their effectiveness in reducing overall carbon emissions. By comparing these innovative solutions with conventional systems, the study will provide insights into the potential of these technologies to contribute to global carbon reduction goals.

1.4 Scope of the Report

This report will focus on the environmental sustainability and social acceptance of various innovative retrofit technologies used in existing buildings. The technologies to be analysed



include bio-aerogel insulation panels, PV vacuum glazing units, prefabricated insulation panels, phase change material (PCM) panels, solar-assisted heat pumps, ground source heat pumps, evaporative cooling units, window heat recovery units, solar PV/T panels, and daylight louvers. The scope of the analysis will cover the entire life cycle of these technologies, including manufacturing, installation, operational use, and end-of-life stages. The report will compare the carbon emissions of these innovative technologies with those of conventional systems, providing a detailed evaluation of their environmental performance. Additionally, the report will consider the broader implications of adopting these technologies, including their cost-effectiveness, ease of implementation, and potential barriers to social acceptance.

In summary, this study will provide a comprehensive assessment of the potential carbon savings achievable through the use of innovative building retrofit technologies, offering valuable insights for policymakers, industry professionals, and other stakeholders interested in promoting sustainable building practices.

2 Methodology

2.1 Description of the life cycle assessment (LCA) methodology.

The Life Cycle Assessment (LCA) methodology is a systematic approach used to evaluate the environmental impacts associated with all stages of a product's life cycle, from raw material extraction through production, use, and disposal (cradle-to-grave). In the context of assessing the life cycle carbon emission savings for building retrofits, the LCA methodology provides a comprehensive framework to quantify and compare the carbon emissions of innovative technologies versus conventional systems.

2.1.1 Goal and Scope Definition

- **Objective:** The primary objective of this LCA is to assess and compare the life cycle carbon emissions of innovative retrofit technologies with conventional building systems. This will help determine the potential carbon savings achievable through the use of innovative technologies.
- **System Boundaries:** The LCA will cover all stages of the product life cycle, including:
 - **Raw Material Extraction:** Extraction of raw materials required for the production of the components of each system.
 - **Manufacturing:** The energy and material inputs needed to manufacture the systems.
 - **Transportation:** The emissions associated with transporting materials and finished products to the installation site.
 - **Installation:** The carbon emissions related to the installation of the systems in existing buildings.
 - **Use Phase:** The operational emissions, including energy consumption and maintenance over the life of the systems.
 - **End-of-Life:** The disposal, recycling, or reuse of materials at the end of the product's life.
- **Functional Unit:** The functional unit defines the basis for comparison between the different systems. In this assessment, the functional unit is typically defined as the carbon emissions per square meter of building area over a specified time period (e.g., 50 years). This allows for consistent comparisons between different technologies and systems.

2.1.2 Life Cycle Inventory (LCI)

- **Data Collection:** This phase involves collecting data on all relevant inputs and outputs for each life cycle stage. This includes:
 - **Energy Consumption:** Quantifying the energy required at each stage, including production, transportation, and operation.
 - **Material Inputs:** Identifying and quantifying the raw materials used, including their sources and quantities.
 - **Emissions Data:** Recording the emissions to air, water, and land, particularly focusing on carbon dioxide (CO₂) and other greenhouse gases (GHGs) that contribute to global warming.

- **Data Sources:** The LCI will rely on a combination of primary data (from manufacturers, installation contractors, and operation records) and secondary data (from databases such as **ecoinvent** or literature reviews).

2.1.3 Life Cycle Impact Assessment (LCIA)

- **Impact Categories:** In this assessment, the primary focus is on the global warming potential (GWP), which quantifies the carbon footprint of each system. Other environmental impacts, such as resource depletion, acidification, and ozone depletion, can also be considered as part of a broader analysis.
- **Characterization Factors:** The GWP is calculated using characterization factors that convert emissions of various greenhouse gases into CO₂-equivalents (CO₂e). This allows for a single metric comparison across different technologies.
- **Normalization and Weighting:** To facilitate comparison, results may be normalized against a reference scenario (e.g., conventional systems) and weighted to reflect the relative importance of carbon savings.

2.1.4 Interpretation

- **Result Analysis:** The results of the LCIA are analysed to identify key contributors to carbon emissions across the life cycle stages. This includes identifying which stages or processes are the most carbon-intensive and how the innovative technologies perform relative to conventional systems.
- **Uncertainty and Sensitivity Analysis:** Acknowledging the uncertainties in data and assumptions, a sensitivity analysis is conducted to assess how variations in key parameters (e.g., energy mix, material sourcing) impact the overall results.
- **Conclusions and Recommendations:** Based on the analysis, conclusions are drawn regarding the effectiveness of the innovative technologies in reducing life cycle carbon emissions. Recommendations are made for optimizing the retrofit process and improving the environmental performance of building systems

2.2 System boundaries: Cradle-to-grave analysis, including manufacturing, installation, operational, and end-of-life stages.

The system boundaries in a Life Cycle Assessment (LCA) define the scope of the analysis, encompassing all the stages of a product or system's life cycle. In this study, the system boundaries are set to include a cradle-to-grave analysis, which covers the entire life span of the innovative retrofit technologies as well as conventional systems. This comprehensive approach ensures that all relevant carbon emissions are accounted for, from the initial extraction of raw materials to the final disposal or recycling of the system components.

2.2.1 Raw Material Extraction

- Scope: This stage includes the extraction of all raw materials required to produce the components of the building systems. This encompasses mining, logging, and other resource extraction activities.
- Carbon Emissions: Emissions result from the energy consumed during extraction processes and the transportation of raw materials to manufacturing facilities. These emissions contribute to the overall carbon footprint of the system.

2.2.2 Manufacturing

- Scope: The manufacturing stage covers the processing of raw materials into finished products, including all intermediate processes and the assembly of components.
- Carbon Emissions: Emissions arise from the energy consumed in manufacturing plants, the use of auxiliary materials (e.g., adhesives, coatings), and waste generated during production. Manufacturing is often a significant contributor to the life cycle carbon footprint, especially for materials-intensive products like insulation panels and glazing units.

2.2.3 Transportation

- Scope: Transportation is considered at multiple points within the system boundaries: transporting raw materials to manufacturing sites, moving finished products to distribution centres, and delivering materials to the installation site.
- Carbon Emissions: Emissions are associated with the fuel consumption of transportation vehicles (trucks, ships, etc.). The distance and mode of transportation (e.g., road, sea, rail) influence the carbon footprint at this stage.

2.2.4 Installation

- Scope: The installation stage involves the integration of the retrofit technologies into the existing building structure. This includes any preparatory work, labour, and the use of additional materials like fasteners, sealants, or scaffolding.
- Carbon Emissions: Emissions at this stage primarily come from the energy used by tools and machinery during installation, transportation of workers and materials to the site, and waste generated from off-cuts and packaging materials.

2.2.5 Operational Stage

- Scope: The operational stage covers the entire period during which the building systems are in use. This includes energy consumption for heating, cooling, lighting, and other building services, as well as routine maintenance and repair activities.
- Carbon Emissions: The operational stage typically contributes the largest share of the life cycle carbon emissions, particularly in energy-intensive systems. For innovative technologies like solar-assisted heat pumps or ground source heat pumps, operational emissions are a critical factor in evaluating their carbon savings potential compared to conventional systems.



2.2.6 End-of-Life (EoL)

- **Scope:** The end-of-life stage includes the processes involved in decommissioning the systems at the end of their useful life. This involves dismantling, transportation to disposal or recycling facilities, and final waste treatment.
- **Carbon Emissions:** Emissions at this stage arise from the energy consumed during dismantling and transportation, as well as emissions from landfilling, incineration, or recycling processes. The ability to recycle materials can significantly reduce the carbon footprint, and the choice between landfilling versus recycling is an important consideration in the LCA.

2.2.7 System Boundary Exclusions

- **Non-Operational Occupant Activities:** Activities and energy use not directly related to the building systems being assessed (e.g., occupant appliances, personal electronics) are typically excluded from the system boundaries.
- **Secondary Effects:** Indirect impacts, such as changes in indoor air quality or thermal comfort that do not directly relate to carbon emissions, are generally not included unless they have a significant effect on energy use.

By defining these system boundaries, the LCA can comprehensively account for all relevant sources of carbon emissions throughout the life cycle of the building systems, enabling a fair comparison between innovative retrofit technologies and conventional alternatives. This cradle-to-grave approach ensures that the analysis captures the full environmental impact, providing a robust basis for assessing the carbon savings potential of each technology.

2.3 Functional unit definition (e.g., per square meter of building space, per year).

The functional unit in a Life Cycle Assessment (LCA) serves as a reference point for comparing the environmental impacts of different systems or products. It provides a standardized measure to ensure that comparisons between innovative retrofit technologies and conventional systems are meaningful and consistent. For this assessment, the functional unit is defined as follows:

Functional Unit: Carbon Emissions per Square Meter of Building Space per Year

This functional unit is selected to reflect the typical performance of building retrofit technologies in reducing carbon emissions relative to the area of the building being retrofitted and the time over which the technologies operate. The key aspects of this functional unit are described below:

2.3.1 Per Square Meter of Building Space

Scope: The functional unit is normalized per square meter (m²) of the building's floor area. This allows for a direct comparison of the carbon emissions associated with retrofitting different-sized buildings or portions of a building.

Rationale: Buildings vary widely in size, and the energy demands (heating, cooling, etc.) are often proportional to the floor area. Using a per square meter metric ensures that the results are scalable and applicable to a variety of building types and sizes



2.3.2 Per Year

Scope: The functional unit is further normalized on an annual basis, reflecting the carbon emissions savings or impacts over one year of operation.

Rationale: Building retrofit technologies have long operational lives, often spanning several decades. Normalizing emissions on a per-year basis allows for the evaluation of the performance and benefits of the technologies over time, taking into account both initial installation impacts and ongoing operational emissions.

2.3.3 Considerations in the Functional Unit Definition

Lifetime Considerations: Although the functional unit is per year, the assessment will consider the entire operational lifetime of the technologies to calculate annualized emissions. For instance, if a system has a 25-year lifespan, the total life cycle emissions will be divided by 25 to determine the annual emissions per square meter.

2.3.4 Building Energy Demand

The functional unit assumes that energy demand is consistent with typical building usage patterns, which may vary based on location, building type, and climate. The analysis will account for these variations to ensure that the functional unit remains applicable across different scenarios.

Technology Comparisons: By using carbon emissions per square meter per year as the functional unit, the study can directly compare the effectiveness of various retrofit technologies in reducing the carbon footprint of a building. This comparison will highlight the relative carbon savings of each technology when applied to a standard unit of building space over a typical operational period.

This functional unit provides a clear, standardized basis for assessing and comparing the carbon emissions performance of innovative retrofit technologies against conventional systems, ensuring that the findings are relevant, scalable, and actionable for stakeholders in the building industry.

2.4 Data sources and assumptions.

In a Life Cycle Assessment (LCA), accurate and reliable data are critical for assessing the environmental impacts of the systems under study. The quality of the data directly influences the credibility of the results. For this assessment of the life cycle carbon emission savings for building retrofits, data will be drawn from various sources, and certain assumptions will be made to fill gaps where data are unavailable or uncertain. Below is a description of the data sources and assumptions used in this study:



2.4.1 Primary Data Sources

- **Manufacturer Specifications:** Data will be sourced directly from manufacturers of the innovative retrofit technologies and conventional systems. This includes energy consumption rates, material composition, and manufacturing processes. For example, manufacturers of bio-aerogel insulation panels or ground source heat pumps will provide details on energy inputs during production and material sourcing.
- **Installation Contractors:** Information on the installation processes, including the energy used by machinery and transportation of materials, will be gathered from installation contractors and case studies. This data will help estimate the carbon footprint associated with the installation phase.
- **Operational Data:** Real-world operational data, such as energy consumption during the use phase, will be collected from existing installations of the technologies or from building energy management systems. This data is crucial for assessing the long-term performance and carbon emissions of the technologies.

2.4.2 Secondary Data Sources

- **LCA Databases:** Established life cycle assessment databases such as Ecoinvent, GaBi, and SimaPro will provide secondary data for processes where primary data is not available. These databases contain detailed information on the environmental impacts of materials, energy sources, and processes used in the construction industry.
- **Literature Reviews:** Academic journals, industry reports, and technical publications will be reviewed to supplement primary data, especially for innovative technologies that may not have extensive real-world data available. Peer-reviewed studies on the life cycle impacts of similar technologies will be particularly valuable.
- **Government and Industry Standards:** Data will be drawn from government publications, industry standards, and guidelines, such as those provided by the International Organization for Standardization (ISO) or the Building Research Establishment Environmental Assessment Method (BREEAM). These sources provide standardized values for emissions factors, energy efficiency, and other relevant metrics.

2.4.3 Assumptions

- **Material Longevity and Durability:** Assumptions will be made regarding the expected lifespan of materials and technologies. For instance, insulation panels may be assumed to last for 25-50 years, while PV glazing units might be expected to have a 20-30 year operational life. These assumptions will be based on manufacturer warranties, industry norms, and literature.
- **Energy Mix:** The carbon intensity of the energy used during the operational phase will be based on the average energy mix of the region where the building is located. If specific regional data is unavailable, national averages will be used. For example, a building in Europe might assume a certain percentage of renewable energy sources in its operational energy mix.



- **End-of-Life Scenarios:** Assumptions will be made about the end-of-life treatment of materials, such as the percentage of materials that are recycled, landfilled, or incinerated. These assumptions will be based on industry practices and recycling rates reported in literature.
- **Transportation Distances:** Assumptions regarding transportation distances for materials from the manufacturing site to the installation location will be made based on typical supply chain logistics. If exact distances are not known, average distances based on similar projects will be used.
- **Operational Efficiency Over Time:** It will be assumed that the efficiency of operational technologies, such as heat pumps and solar panels, may degrade over time. A certain percentage of efficiency loss per year will be applied based on industry averages.

2.4.4 Uncertainty and Sensitivity Analysis

- **Data Gaps and Uncertainty:** In cases where data is uncertain or incomplete, assumptions will be made to fill these gaps. The potential impact of these assumptions on the overall results will be assessed through sensitivity analysis. This analysis will explore how variations in key assumptions (e.g., lifespan, energy mix, transportation distances) affect the LCA outcomes.
- **Scenario Analysis:** Multiple scenarios may be developed to assess the impact of different assumptions. For instance, a best-case and worst-case scenario could be modelled for the operational phase energy mix to understand the potential range of carbon emissions.

2.4.5 Data Validation

- **Cross-Verification:** Whenever possible, data from multiple sources will be cross-verified to ensure accuracy and consistency. For example, operational energy consumption data from manufacturer specifications will be compared with real-world case studies to validate performance claims.
- **Expert Consultation:** Industry experts and stakeholders will review assumptions and data interpretations to ensure they are reasonable and reflect current best practices.

By clearly defining the data sources and assumptions, this LCA ensures that the results are robust, transparent, and reflective of real-world conditions, enabling a credible comparison of the carbon emission savings between innovative retrofit technologies and conventional systems.

2.5 Comparative analysis framework

The comparative analysis framework is designed to systematically evaluate and contrast the life cycle carbon emissions of innovative retrofit technologies against conventional systems. This framework ensures a fair and comprehensive assessment, allowing for a meaningful comparison of the carbon savings potential offered by the innovative technologies. The comparison will be conducted across several key dimensions, using consistent metrics and assumptions to ensure validity and reliability.



2.5.1 Selection of Conventional Systems

- **Baseline Systems:** Conventional building systems that represent the current standard practices in the industry will be selected as the baseline for comparison. These systems might include traditional insulation materials (e.g., fiberglass or mineral wool), double-glazed windows, standard gas or electric heating systems, conventional air conditioning units, and non-renewable energy sources.
- **Performance Benchmarks:** The performance characteristics of these conventional systems will be established based on industry standards, manufacturer data, and real-world operational data. This will include energy efficiency ratings, carbon emissions, and material lifespans.

2.5.2 Life Cycle Stages for Comparison

- **Cradle-to-Grave Comparison:** Both innovative and conventional systems will be assessed across the full life cycle, including raw material extraction, manufacturing, transportation, installation, operational use, and end-of-life disposal or recycling. This cradle-to-grave approach ensures that all carbon emissions are captured, and that the comparison is comprehensive.
- **Stage-Specific Analysis:** Each life cycle stage will be analysed separately, allowing for the identification of which stages contribute the most to the overall carbon footprint. This stage-specific analysis will provide insights into where innovative technologies offer the most significant carbon savings.

2.5.3 Key Performance Indicators (KPIs)

- **Global Warming Potential (GWP):** The primary metric for comparison will be the Global Warming Potential, expressed in CO₂-equivalents (CO₂e). This metric will quantify the total carbon emissions associated with each system over its life cycle.
- **Energy Efficiency:** The operational energy efficiency of each system will be compared, as this directly influences the carbon emissions during the use phase. Metrics such as Energy Use Intensity (EUI) and Seasonal Energy Efficiency Ratio (SEER) will be used where applicable.
- **Material Efficiency:** The material composition and resource efficiency of each system will be evaluated to determine the carbon emissions associated with raw material extraction and manufacturing.
- **Payback Period:** The time required for the innovative technologies to achieve carbon savings that offset the emissions from their production and installation will be calculated. This metric helps assess the long-term environmental benefits.

2.5.4 Normalization of Results

- **Functional Unit Normalization:** All results will be normalized to a common functional unit, defined as carbon emissions per square meter of building space per year. This allows for a direct comparison of the carbon savings across different technologies and building scenarios.



- **Time Horizon:** A consistent time horizon, typically 25 to 50 years, will be used to compare the operational emissions of the systems. This time frame reflects the expected lifespan of building systems and ensures that long-term impacts are considered.

2.5.5 Scenario Analysis

- **Base Case Scenario:** A base case scenario will be established using standard assumptions about building usage, energy mix, and material lifespans. This scenario will serve as the reference point for all comparisons.
- **Alternative Scenarios:** To account for variability in real-world conditions, alternative scenarios will be developed. These might include variations in energy grid composition (e.g., increased use of renewable energy), different climate zones (affecting heating and cooling demands), or varying levels of maintenance and operational efficiency.
- **Best-Case vs. Worst-Case:** Best-case and worst-case scenarios will be modelled to understand the range of potential outcomes. These scenarios will help to identify under what conditions innovative technologies offer the most significant advantages over conventional systems.

2.5.6 Sensitivity Analysis

- **Parameter Sensitivity:** A sensitivity analysis will be conducted to evaluate how changes in key parameters (e.g., energy prices, material degradation rates, installation practices) impact the comparative results. This analysis helps identify which factors are most critical in determining the carbon savings of each system.
- **Uncertainty Assessment:** The sensitivity analysis will also address uncertainties in the data and assumptions, providing a range of possible outcomes rather than a single deterministic result.

2.5.7 Comparative Interpretation

- **Relative Performance Ranking:** The innovative technologies will be ranked based on their carbon savings potential compared to conventional systems. This ranking will consider both the total carbon savings and the efficiency of the savings relative to the investment in new technologies.
- **Trade-Offs Analysis:** The analysis will identify any trade-offs, such as higher upfront carbon emissions from manufacturing or higher costs that may offset the long-term benefits of innovative technologies.
- **Recommendations:** Based on the comparative analysis, recommendations will be made for the most effective technologies in specific building retrofit scenarios. These recommendations will consider not only carbon savings but also factors such as cost-effectiveness, ease of installation, and compatibility with existing building systems.

By following this comparative analysis framework, the report will provide a clear and structured evaluation of how innovative retrofit technologies perform relative to conventional systems, offering actionable insights for decision-makers in the building industry.



3 Innovative Technologies Overview

3.1 Bio-aerogel Insulation Panel

- **Description and Properties:** Bio-aerogel insulation panels are advanced materials composed of aerogels derived from biogenic sources, such as cellulose or other natural fibres. These panels are characterized by their extremely low thermal conductivity, making them one of the most effective thermal insulators available. The porous structure of aerogels provides exceptional insulation properties while maintaining a lightweight form factor. Bio-aerogels are also hydrophobic, which helps in moisture resistance, and they are non-combustible, enhancing their safety profile. Additionally, these materials are sustainable and biodegradable, making them environmentally friendly.
- **Applications in Building Retrofits:** In building retrofits, bio-aerogel insulation panels can be applied to walls, roofs, and floors to significantly improve the thermal efficiency of existing structures. They are particularly useful in situations where space is limited, as their high insulation performance allows for thinner panels compared to traditional insulation materials. Retrofitting with bio-aerogel panels can reduce heating and cooling demands, leading to lower energy consumption and carbon emissions. These panels are suitable for both residential and commercial buildings, especially in projects aiming for high-performance energy efficiency or net-zero energy goals.

3.2 PV Vacuum Glazing Unit

- **Description and Properties:** Photovoltaic (PV) vacuum glazing units are innovative window systems that integrate photovoltaic cells within a vacuum-insulated glazing assembly. The vacuum between the glass panes provides excellent thermal insulation by minimizing heat transfer, while the embedded PV cells convert sunlight into electricity. These units combine the benefits of high energy efficiency with renewable energy generation. The vacuum insulation significantly reduces heat loss and solar heat gain, while the PV cells contribute to the building's energy supply.
- **Applications in Building Retrofits:** PV vacuum glazing units are ideal for retrofitting windows in buildings aiming to improve energy efficiency and incorporate renewable energy solutions. They are particularly beneficial in urban environments where roof space for traditional solar panels may be limited. By replacing existing windows with PV vacuum glazing, buildings can reduce heating and cooling loads while generating electricity on-site, contributing to overall carbon reduction. These units are suitable for both residential and commercial buildings, especially in high-rise structures where window area is substantial.

3.3 Prefabricated Insulation Panels

- **Description and Properties:** Prefabricated insulation panels are modular building components that come pre-manufactured with integrated insulation materials. These panels can be made from a variety of materials, including expanded polystyrene (EPS), polyurethane (PUR), and mineral wool, combined with rigid outer layers, such as plywood or metal. The prefabrication process ensures consistent quality and reduces on-site labour. These panels are designed for



quick installation, with interlocking systems that ensure airtightness and minimize thermal bridging.

- **Applications in Building Retrofits:** Prefabricated insulation panels are widely used in retrofitting projects to upgrade the thermal performance of building envelopes. They can be applied to external walls, roofs, and floors, providing a fast and effective way to improve energy efficiency. These panels are particularly advantageous in retrofits where minimizing disruption to occupants is a priority, as they can be installed quickly and with minimal mess. Prefabricated panels are suitable for a wide range of building types, including residential, commercial, and industrial buildings.

3.4 PCM (Phase Change Material) Panels

- **Description and Properties:** Phase Change Material (PCM) panels are advanced thermal storage systems that absorb, store, and release thermal energy during the material's phase transition between solid and liquid states. PCMs have the ability to store large amounts of energy within a narrow temperature range, which helps to regulate indoor temperatures by absorbing excess heat during the day and releasing it at night. The materials used in PCM panels can include organic compounds, such as paraffin, or inorganic salts.
- **Applications in Building Retrofits:** PCM panels are used in retrofitting to enhance the thermal mass of buildings, which helps in maintaining more stable indoor temperatures and reducing the need for active heating and cooling systems. They can be integrated into walls, ceilings, and floors, or placed behind drywall. By reducing temperature fluctuations, PCM panels contribute to lower energy consumption and greater occupant comfort. These panels are particularly beneficial in climates with significant daily temperature swings and are suitable for residential, commercial, and educational buildings.

3.5 Solar Assisted Heat Pump

- **Description and Properties:** A solar-assisted heat pump combines the principles of a heat pump with solar thermal technology to provide efficient heating and cooling. The system uses a solar collector to preheat the working fluid before it enters the heat pump, thereby increasing the system's efficiency. This hybrid approach allows the heat pump to operate more effectively, especially in colder climates, and reduces the amount of electrical energy required to operate the system.
- **Applications in Building Retrofits:** Solar-assisted heat pumps are used in retrofitting projects to replace conventional heating and cooling systems, offering a significant reduction in energy consumption and carbon emissions. They are particularly suitable for retrofits in buildings with high heating or cooling demands, such as residential homes, hotels, and office buildings. By integrating renewable solar energy into the heating and cooling process, these systems help buildings achieve greater energy independence and reduce reliance on fossil fuels.



3.6 Ground Source Heat Pump

- **Description and Properties:** Ground source heat pumps (GSHPs), also known as geothermal heat pumps, utilize the stable temperatures of the ground to provide heating and cooling for buildings. The system consists of a ground loop, which is buried in the earth, and a heat pump unit that transfers heat between the building and the ground. GSHPs are highly efficient, as the ground temperature remains relatively constant throughout the year, providing a reliable source of thermal energy.
- **Applications in Building Retrofits:** GSHPs are ideal for retrofitting buildings with significant heating and cooling needs, particularly in regions with extreme weather conditions. They can be used in residential, commercial, and institutional buildings, offering a long-term solution for reducing energy consumption and carbon emissions. Retrofitting with GSHPs typically involves installing the ground loop in available outdoor space, such as gardens or parking areas. These systems are particularly effective in buildings with large land areas and can be combined with other renewable energy technologies for further carbon reductions.

3.7 Evaporative Cooling Units

- **Description and Properties:** Evaporative cooling units cool air by passing it over water-saturated pads, causing the water to evaporate and absorb heat from the air. This process provides cooling using significantly less energy than traditional air conditioning systems, as it relies on the natural cooling effect of evaporation rather than mechanical refrigeration. Evaporative coolers are most effective in hot, dry climates where humidity is low.
- **Applications in Building Retrofits:** In building retrofits, evaporative cooling units are an energy-efficient alternative to conventional air conditioning, particularly in regions with dry climates. They can be installed in residential and commercial buildings, often as rooftop or window-mounted units. These systems are especially advantageous for retrofitting older buildings where the installation of conventional air conditioning systems may be impractical or too costly. By reducing energy consumption for cooling, evaporative coolers contribute to lower carbon emissions and operational costs.

3.8 Window Heat Recovery Unit

- **Description and Properties:** Window heat recovery units are compact systems installed within window frames that capture and recycle heat from exhaust air while bringing in fresh air. These units use heat exchangers to transfer thermal energy from the outgoing air to the incoming air, significantly improving the energy efficiency of ventilation systems. Window heat recovery units are particularly useful in reducing heat loss in winter and minimizing the cooling load in summer.
- **Applications in Building Retrofits:** Window heat recovery units are ideal for retrofitting buildings where space for traditional heat recovery ventilation systems is limited. They can be installed in both residential and commercial buildings, particularly in urban environments where maintaining indoor air quality and energy efficiency is critical. These units are well-suited for retrofitting older buildings with poor ventilation systems, offering a straightforward way to improve thermal comfort and reduce heating and cooling costs.



3.9 Solar PV/T (Photovoltaic/Thermal) Panels

- **Description and Properties:** Solar PV/T panels are hybrid systems that generate both electricity and thermal energy from a single solar panel. These systems combine photovoltaic cells for electricity generation with a thermal collector that absorbs the excess heat generated by the PV cells, which can be used for domestic hot water or space heating. This dual-functionality enhances the overall energy efficiency of the solar panel and maximizes the use of available roof space.
- **Applications in Building Retrofits:** Solar PV/T panels are an excellent choice for retrofitting buildings where both electricity and hot water or heating are needed. They are particularly effective in residential and commercial buildings with limited roof space, as they allow for the simultaneous generation of multiple forms of energy from a single installation. Retrofitting with PV/T panels can significantly reduce reliance on external energy sources, lower utility bills, and contribute to overall carbon reduction goals.

3.10 Daylight Louvers

- **Description and Properties:** Daylight louvers are adjustable shading devices installed on the exterior or interior of windows to control the amount of natural light entering a building. These louvers can be manually or automatically adjusted to optimize daylighting, reduce glare, and minimize the need for artificial lighting. They are designed to redirect sunlight deeper into building interiors while blocking direct solar gain, which helps to reduce cooling loads.
- **Applications in Building Retrofits:** Daylight louvers are used in retrofitting projects to enhance natural lighting while improving energy efficiency. They are particularly beneficial in buildings with large windows or in areas with high solar exposure. By reducing the reliance on artificial lighting, daylight louvers can lower electricity consumption and improve occupant comfort. These systems are suitable for a wide range of buildings, including offices, schools, and residential buildings, where optimizing natural light is a priority.

This overview of innovative technologies demonstrates their potential to significantly improve the energy efficiency and reduce the carbon footprint of existing buildings. Each technology offers unique benefits and can be strategically applied in retrofitting projects to meet specific energy and environmental goals.

4 Life Cycle Carbon Emission Analysis

4.1 Baseline (Conventional Systems)

4.1.1 Description of Conventional Systems Used for Comparison

The baseline for this study is established using five pilot buildings located in different European countries: Finland, Greece, Portugal, Spain, and the United Kingdom. These buildings are representative of typical older residential structures that do not meet current energy efficiency standards and rely on conventional systems for heating, cooling, and ventilation.

- Finland (Helsinki): A large apartment building utilizing district heating for space heating and mechanical exhaust ventilation without heat recovery. Some renovations have been made, such as window replacements.
- Greece (Athens): A small apartment building heated by an oil boiler, with cooling provided by electric air conditioners. Ventilation is natural, with solar boilers for domestic hot water.
- Portugal (Mafra): A social house with no central heating or cooling systems, using a portable electric heater for heating and a gas boiler for hot water.
- Spain (Valladolid): A terraced house where heating is provided by independent gas boilers and electric heaters. The building lacks mechanical ventilation, relying on natural ventilation.
- United Kingdom (Nottingham): A semi-detached house with central gas heating supplemented by a portable electric heater, and electric water heating for domestic hot water.

These systems are characterized by lower energy efficiency and higher carbon emissions compared to modern, innovative technologies. They heavily rely on fossil fuels, such as natural gas and oil, and lack advanced energy-saving technologies like heat recovery or renewable energy integration.

Table 1 provides a summary of the baseline annual energy consumption for five buildings located in different countries, detailing both heating and electricity usage. It includes the calculated floor area for each building, the type of heating source used (district heating, oil heating, or natural gas heating), and the annual heating energy consumption measured in kWh per square meter. Additionally, it lists the electricity source (grid electricity) and the corresponding annual electricity consumption in kWh per square meter. For instance, the Finnish building has the largest floor area of 5260 m² and uses district heating with an annual heating energy consumption of 133.6 kWh/m², while the UK building has the highest heating energy consumption at 182.3 kWh/m² using natural gas. The table highlights the variation in energy consumption across different regions and systems.



	Calculated floor area	Heating source	Annual Heating energy	Electricity source	Annual electricity energy
Finland	5260 m ²	District heating	133.6 kWh/m ²	Grid electricity	30.0 kWh/m ²
Greece	172.7 m ²	Oil heating	36.8 kWh/m ²	Grid electricity	14.8 kWh/m ²
Portugal	76.5 m ²	Oil heating	18.3 kWh/m ²	Grid electricity	97.1 kWh/m ²
Spain	198 m ²	Natural gas heating	115.0 kWh/m ²	Grid electricity	19.4 kWh/m ²
UK	107.8 m ²	Natural gas heating	182.3 kWh/m ²	Grid electricity	24.5 kWh/m ²

Table 1 Summary of the baseline annual energy consumption for five buildings

4.1.2 Carbon Emissions Profile Over the Life Cycle of Conventional Systems

The life cycle carbon emissions for these conventional systems are significant and vary depending on the building's location, energy source, and specific characteristics:

4.1.2.1 Manufacturing and Installation:

- Carbon emissions are generated during the production and installation of heating and cooling systems, such as boilers, radiators, and air conditioners. Although these emissions are generally lower than those during the operational phase, they still contribute to the overall carbon footprint.

4.1.2.2 Operational Phase:

The operational phase is the largest contributor to carbon emissions. For instance:

- **Finland:** District heating results in lower emissions compared to other regions due to the use of low-emission sources like nuclear and renewable energy.
- **Greece and Portugal:** High emissions are associated with oil heating and electric systems, particularly given the high carbon intensity of the electricity grid in Greece.
- **Spain and UK:** These buildings rely on natural gas heating, with substantial emissions due to the combustion of fossil fuels for heating.

4.1.2.3 End-of-Life:

- At the end of their life cycle, conventional systems may be replaced or decommissioned, contributing additional, though generally smaller, emissions through the disposal or recycling of materials.

4.1.3 Summary of Baseline Annual Carbon Emissions

- Finland: 161,495.2 kg CO₂/year
- Greece: 22,910.4 kg CO₂/year
- Portugal: 21,051.5 kg CO₂/year
- Spain: 55,369.6 kg CO₂/year
- United Kingdom: 46,234.9 kg CO₂/year

4.1.4 Summary of Baseline Annual Carbon Emissions (Breakdown)

Below is a detailed breakdown of the baseline annual carbon emissions for each of the five pilot buildings. The emissions are categorized by their source—heating and electricity—providing a clear view of the major contributors to the overall carbon footprint.

4.1.4.1 Finland (Helsinki)

- Calculated Floor Area: 5260 m²
- Heating Source: District heating
- Electricity Source: Grid electricity
- Annual Heating Energy: 133.6 kWh/m²
- Annual Electricity Energy: 30.0 kWh/m²
- Heating CO₂ Emissions: $133.6 \text{ kWh/m}^2 \times 5260 \text{ m}^2 \times 0.178 \text{ kg CO}_2/\text{kWh} = 125,087.0 \text{ kg CO}_2/\text{year}$
- Electricity CO₂ Emissions: $30.0 \text{ kWh/m}^2 \times 5260 \text{ m}^2 \times 0.233 \text{ kg CO}_2/\text{kWh} = 36,767.4 \text{ kg CO}_2/\text{year}$
- Total Annual CO₂ Emissions: 161,854.4 kg CO₂/year

4.1.4.2 Greece (Athens)

- Calculated Floor Area: 172.7 m²
- Heating Source: Oil heating
- Electricity Source: Grid electricity
- Annual Heating Energy: 36.8 kWh/m²
- Annual Electricity Energy: 14.8 kWh/m²
- Heating CO₂ Emissions: $36.8 \text{ kWh/m}^2 \times 172.7 \text{ m}^2 \times 0.267 \text{ kg CO}_2/\text{kWh} = 1,696.9 \text{ kg CO}_2/\text{year}$
- Electricity CO₂ Emissions: $14.8 \text{ kWh/m}^2 \times 172.7 \text{ m}^2 \times 0.233 \text{ kg CO}_2/\text{kWh} = 595.5 \text{ kg CO}_2/\text{year}$
- Total Annual CO₂ Emissions: 2,292.4 kg CO₂/year

4.1.4.3 Portugal (Mafra)

- Calculated Floor Area: 76.5 m²



- Heating Source: Oil heating
- Electricity Source: Grid electricity
- Annual Heating Energy: 18.3 kWh/m²
- Annual Electricity Energy: 97.1 kWh/m²
- Heating CO₂ Emissions: $18.3 \text{ kWh/m}^2 \times 76.5 \text{ m}^2 \times 0.267 \text{ kg CO}_2/\text{kWh} = 373.8 \text{ kg CO}_2/\text{year}$
- Electricity CO₂ Emissions: $97.1 \text{ kWh/m}^2 \times 76.5 \text{ m}^2 \times 0.233 \text{ kg CO}_2/\text{kWh} = 1,730.8 \text{ kg CO}_2/\text{year}$
- Total Annual CO₂ Emissions: 2,104.6 kg CO₂/year

4.1.4.4 Spain (Valladolid)

- Calculated Floor Area: 198 m²
- Heating Source: Natural gas heating
- Electricity Source: Grid electricity
- Annual Heating Energy: 115.0 kWh/m²
- Annual Electricity Energy: 19.4 kWh/m²
- Heating CO₂ Emissions: $115.0 \text{ kWh/m}^2 \times 198 \text{ m}^2 \times 0.204 \text{ kg CO}_2/\text{kWh} = 4,645.1 \text{ kg CO}_2/\text{year}$
- Electricity CO₂ Emissions: $19.4 \text{ kWh/m}^2 \times 198 \text{ m}^2 \times 0.233 \text{ kg CO}_2/\text{kWh} = 895.0 \text{ kg CO}_2/\text{year}$
- Total Annual CO₂ Emissions: 5,540.1 kg CO₂/year

4.1.4.5 United Kingdom (Nottingham)

- Calculated Floor Area: 107.8 m²
- Heating Source: Natural gas heating
- Electricity Source: Grid electricity
- Annual Heating Energy: 182.3 kWh/m²
- Annual Electricity Energy: 24.5 kWh/m²
- Heating CO₂ Emissions: $182.3 \text{ kWh/m}^2 \times 107.8 \text{ m}^2 \times 0.204 \text{ kg CO}_2/\text{kWh} = 4,009.0 \text{ kg CO}_2/\text{year}$
- Electricity CO₂ Emissions:
 $24.5 \text{ kWh/m}^2 \times 107.8 \text{ m}^2 \times 0.233 \text{ kg CO}_2/\text{kWh} = 615.4 \text{ kg CO}_2/\text{year}$
- Total Annual CO₂ Emissions: 4,624.4 kg CO₂/year

This detailed breakdown highlights that the operational phase, particularly heating, is the dominant source of carbon emissions in these buildings. The emissions vary significantly across different locations, largely due to differences in heating sources and the carbon intensity of the local electricity grid. The calculation results shown in Table 2.



Country	Calculated Floor Area (m ²)	Heating Source	Electricity Source	Annual Heating Energy (kWh/m ²)	Annual Electricity Energy (kWh/m ²)	Heating CO ₂ Emissions (kg CO ₂ /year)	Electricity CO ₂ Emissions (kg CO ₂ /year)	Total Annual CO ₂ Emissions (kg CO ₂ /year)
Finland	5260	District heating	Grid electricity	133.6	30.0	125,087.0	36,767.4	161,854.4
Greece	172.7	Oil heating	Grid electricity	36.8	14.8	1,696.9	595.5	2,292.4
Portugal	76.5	Oil heating	Grid electricity	18.3	97.1	373.8	1,730.8	2,104.6
Spain	198	Natural gas heating	Grid electricity	115.0	19.4	4,645.1	895.0	5,540.1
United Kingdom	107.8	Natural gas heating	Grid electricity	182.3	24.5	4,009.0	615.4	4,624.4

Table 2 Breakdown of Annual Energy consumption and Carbon emission for each building pilot

4.2 Innovative Technologies

4.2.1 Carbon emissions analysis for each innovative technology:

This analysis is based on the data provided by the respective manufacturers for each innovative technology. The analysis covers the carbon emissions across the manufacturing, installation, operational, and end-of-life stages for each unit of the technologies listed.

4.2.1.1 Bio-aerogel Insulation Panel

- Manufacturer: University of Nottingham
- Unit: Per square meter (m²)
- Manufacturing Emissions: 10 kg CO₂/m²
- Installation Emissions: 2 kg CO₂/m²
- Operational Savings: 20 kg CO₂/m²/year
- End-of-Life Emissions: 0 kg CO₂/m²

4.2.1.2 PV Vacuum Glazing Unit

- Manufacturer: University of Nottingham



- Unit: Per window (m^2 of glazing)
- Manufacturing Emissions: 50 kg CO_2/m^2
- Installation Emissions: 5 kg CO_2/m^2
- Operational Savings: 2 kg $\text{CO}_2/\text{m}^2/\text{year}$
- End-of-Life Emissions: 10 kg CO_2/m^2

4.2.1.3 Prefabricated Insulation Panels

- Manufacturer: CJR
- Unit: Per square meter (m^2)
- Manufacturing Emissions: 15 kg CO_2/m^2
- Installation Emissions: 3 kg CO_2/m^2
- Operational Savings: 15 kg $\text{CO}_2/\text{m}^2/\text{year}$
- End-of-Life Emissions: 5 kg CO_2/m^2

4.2.1.4 PCM Panels

- Manufacturer: PCM Ltd
- Unit: Per square meter (m^2)
- Manufacturing Emissions: 20 kg CO_2/m^2
- Installation Emissions: 2 kg CO_2/m^2
- Operational Savings: 10 kg $\text{CO}_2/\text{m}^2/\text{year}$
- End-of-Life Emissions: 5 kg CO_2/m^2

4.2.1.5 Solar Assisted Heat Pump

- Manufacturer: Arkaya Energy Ltd
- Unit: Per system (per unit)
- Manufacturing Emissions: 200 kg CO_2/unit
- Installation Emissions: 30 kg CO_2/unit
- Operational Savings: 3000 kg $\text{CO}_2/\text{year}/\text{unit}$
- End-of-Life Emissions: 50 kg CO_2/unit

4.2.1.6 Ground Source Heat Pump

- Manufacturer: Arkaya Energy Ltd
- Unit: Per system (per unit)
- Manufacturing Emissions: 500 kg CO_2/unit
- Installation Emissions: 200 kg CO_2/unit
- Operational Savings: 4000 kg $\text{CO}_2/\text{year}/\text{unit}$
- End-of-Life Emissions: 100 kg CO_2/unit



4.2.1.7 Evaporative Cooling Units

- Manufacturer: University of Nottingham
- Unit: Per system (per unit)
- Manufacturing Emissions: 50 kg CO₂/unit
- Installation Emissions: 10 kg CO₂/unit
- Operational Savings: 500 kg CO₂/year/unit
- End-of-Life Emissions: 10 kg CO₂/unit

4.2.1.8 Window Heat Recovery Unit

- Manufacturer: University of Nottingham
- Unit: Per window unit (per unit)
- Manufacturing Emissions: 30 kg CO₂/unit
- Installation Emissions: 5 kg CO₂/unit
- Operational Savings: 200 kg CO₂/year/unit
- End-of-Life Emissions: 10 kg CO₂/unit

4.2.1.9 Solar PV/T Panels

- Manufacturer: SOLIMPEKS
- Unit: Per panel (m² of panel)
- Manufacturing Emissions: 150 kg CO₂/m²
- Installation Emissions: 20 kg CO₂/m²
- Operational Savings: 300 kg CO₂/m²/year
- End-of-Life Emissions: 50 kg CO₂/m²

4.2.1.10 Daylight Louvers

- Manufacturer: Koester
- Unit: Per louver (per unit)
- Manufacturing Emissions: 10 kg CO₂/unit
- Installation Emissions: 2 kg CO₂/unit
- Operational Savings: 50 kg CO₂/year/unit
- End-of-Life Emissions: 5 kg CO₂/unit

The data provided by the manufacturers indicates that each innovative technology offers varying degrees of carbon emission reductions across its life cycle stages. The operational phase generally provides the most significant carbon savings, with reductions in heating, cooling, and electricity consumption contributing to lower overall emissions. The manufacturing and end-of-life phases contribute smaller amounts of emissions, with some technologies like bio-aerogel insulation and evaporative cooling units showing particularly low impact in these stages.



4.3 Comparative analysis: Summarizing and contrasting the carbon emissions of each innovative technology with conventional systems.

This section provides a detailed comparative analysis of the life cycle carbon emissions for each innovative technology versus conventional systems. The analysis includes the full calculation process for each stage—manufacturing, installation, operational, and end-of-life—and compares the total emissions over a 25-year period.

4.3.1.1 Bio-aerogel Insulation Panel vs. Conventional Insulation (e.g. EPS)

Conventional EPS Insulation:

Manufacturing: 20 kg CO₂/m²

Installation: 5 kg CO₂/m²

Operational: 30 kg CO₂/m²/year

End-of-Life: 10 kg CO₂/m²

Total Over 25 Years: $20 + 5 + (30 \times 25) + 10 = 785$ kg CO₂/m²

Bio-aerogel Insulation Panel:

Manufacturing: 10 kg CO₂/m²

Installation: 2 kg CO₂/m²

Operational: 20 kg CO₂/m²/year

End-of-Life: 0 kg CO₂/m²

Total Over 25 Years: $10 + 2 + (20 \times 25) + 0 = 512$ kg CO₂/m²

Carbon Savings: $785 - 512 = 273$ kg CO₂/m² over 25 years (34.8% reduction)

4.3.1.2 PV Vacuum Glazing Unit vs. Conventional Double-Glazing

Conventional Double-Glazing:

Manufacturing: 25 kg CO₂/m²

Installation: 3 kg CO₂/m²

Operational: 10 kg CO₂/m²/year

End-of-Life: 5 kg CO₂/m²

Total Over 25 Years: $25 + 3 + (10 \times 25) + 5 = 283$ kg CO₂/m²

PV Vacuum Glazing Unit:

Manufacturing: 50 kg CO₂/m²

Installation: 5 kg CO₂/m²

Operational: 2 kg CO₂/m²/year

End-of-Life: 10 kg CO₂/m²

Total Over 25 Years: $50 + 5 + (2 \times 25) + 10 = 115$ kg CO₂/m²



Carbon Savings: $283 - 115 = 2,468 \text{ kg CO}_2/\text{m}^2$ over 25 years (59.4% reduction)

4.3.1.3 Prefabricated Insulation Panels vs. Conventional On-Site Insulation

Conventional On-Site Insulation:

Manufacturing: $20 \text{ kg CO}_2/\text{m}^2$

Installation: $7 \text{ kg CO}_2/\text{m}^2$

Operational: $30 \text{ kg CO}_2/\text{m}^2/\text{year}$

End-of-Life: $10 \text{ kg CO}_2/\text{m}^2$

Total Over 25 Years: $20 + 7 + (30 \times 25) + 10 = 787 \text{ kg CO}_2/\text{m}^2$

Prefabricated Insulation Panels:

Manufacturing: $15 \text{ kg CO}_2/\text{m}^2$

Installation: $3 \text{ kg CO}_2/\text{m}^2$

Operational: $15 \text{ kg CO}_2/\text{m}^2/\text{year}$

End-of-Life: $5 \text{ kg CO}_2/\text{m}^2$

Total Over 25 Years: $15 + 3 + (15 \times 25) + 5 = 398 \text{ kg CO}_2/\text{m}^2$

Carbon Savings: $787 - 398 = 389 \text{ kg CO}_2/\text{m}^2$ over 25 years (49.4% reduction)

4.3.1.4 PCM Panels vs. Conventional Building Materials

Conventional Building Materials:

Manufacturing: $10 \text{ kg CO}_2/\text{m}^2$

Installation: $2 \text{ kg CO}_2/\text{m}^2$

Operational: $20 \text{ kg CO}_2/\text{m}^2/\text{year}$

End-of-Life: $5 \text{ kg CO}_2/\text{m}^2$

Total Over 25 Years: $10 + 2 + (20 \times 25) + 5 = 517 \text{ kg CO}_2/\text{m}^2$

PCM Panels:

Manufacturing: $20 \text{ kg CO}_2/\text{m}^2$

Installation: $2 \text{ kg CO}_2/\text{m}^2$

Operational: $10 \text{ kg CO}_2/\text{m}^2/\text{year}$

End-of-Life: $5 \text{ kg CO}_2/\text{m}^2$

Total Over 25 Year: $20 + 2 + (10 \times 25) + 5 = 277 \text{ kg CO}_2/\text{m}^2$

Carbon Savings: $517 - 402 = 115 \text{ kg CO}_2/\text{m}^2$ over 25 years (46.4% reduction)

4.3.1.5 Solar Assisted Heat Pump vs. Conventional Heat Pump

Conventional Heat Pump:

Manufacturing: $150 \text{ kg CO}_2/\text{unit}$

Installation: $30 \text{ kg CO}_2/\text{unit}$



Operational: 2000 kg CO₂/year/unit

End-of-Life: 20 kg CO₂/unit

Total Over 25 Years: $150 + 30 + (2000 \times 25) + 20 = 50,200$ kg CO₂/unit

Solar Assisted Heat Pump:

Manufacturing: 120 kg CO₂/unit

Installation: 30 kg CO₂/unit

Operational: 880 kg CO₂/year/unit

End-of-Life: 50 kg CO₂/unit

Total Over 25 Years: $200 + 30 + (880 \times 25) + 50 = 22,280$ kg CO₂/unit

Carbon Savings: $50,200 - 22,280 = 27,920$ kg CO₂/unit over 25 years (55.6% reduction)

4.3.1.6 Ground Source Heat Pump vs. Conventional Heat Pump

Conventional Heat Pump:

Manufacturing: 150 kg CO₂/unit

Installation: 30 kg CO₂/unit

Operational: 2000 kg CO₂/year/unit

End-of-Life: 20 kg CO₂/unit

Total Over 25 Years: $150 + 30 + (2000 \times 25) + 20 = 50,200$ kg CO₂/unit

Ground Source Heat Pump:

Manufacturing: 500 kg CO₂/unit

Installation: 200 kg CO₂/unit

Operational: 1160 kg CO₂/year/unit

End-of-Life: 100 kg CO₂/unit

Total Over 25 Years: $500 + 200 + (1160 \times 25) + 100 = 29,800$ kg CO₂/unit

Carbon Savings: $50,200 - 29,800 = 20,400$ kg CO₂/unit over 25 years (40.6% reduction)

4.3.1.7 Evaporative Cooling Units vs. Conventional Air Conditioning

Conventional Air Conditioning:

Manufacturing: 100 kg CO₂/unit

Installation: 20 kg CO₂/unit

Operational: 700 kg CO₂/year/unit

End-of-Life: 30 kg CO₂/unit

Total Over 25 Years: $100 + 20 + (700 \times 25) + 30 = 17,650$ kg CO₂/unit

Evaporative Cooling Units:



Manufacturing: 50 kg CO₂/unit
Installation: 10 kg CO₂/unit
Operational: 250 kg CO₂/year/unit
End-of-Life: 10 kg CO₂/unit
Total Over 25 Years: $50 + 10 + (250 \times 20) + 10 = 5,070$ kg CO₂/unit

Carbon Savings: $17,650 - 5,070 = 12,580$ kg CO₂/unit over 25 years (71.3% reduction)

4.3.1.8 Window Heat Recovery Unit vs. Conventional Ventilation

Conventional Ventilation:

Manufacturing: 20 kg CO₂/unit
Installation: 5 kg CO₂/unit
Operational: 5 kg CO₂/year/unit
End-of-Life: 5 kg CO₂/unit
Total Over 25 Years: $20 + 5 + (5 \times 25) + 5 = 155$ kg CO₂/unit

Window Heat Recovery Unit:

Manufacturing: 15 kg CO₂/unit
Installation: 5 kg CO₂/unit
Operational: 1 kg CO₂/year/unit
End-of-Life: 5 kg CO₂/unit
Total Over 25 Years: $15 + 5 + (1 \times 25) + 5 = 50$ kg CO₂/unit

Carbon Savings: $155 - 50 = 105$ kg CO₂/unit over 25 years (67.7% reduction)

4.3.1.9 Solar PV/T Panels vs. Conventional Solar PV Panels

Conventional Solar PV Panels:

Manufacturing: 100 kg CO₂/m²
Installation: 15 kg CO₂/m²
Operational: -75 kg CO₂/year/m²
End-of-Life: 20 kg CO₂/m²
Total Over 25 Years: $100 + 15 + (-75 \times 25) + 20 = -1,740$ kg CO₂/m²

Solar PV/T Panels:

Manufacturing: 150 kg CO₂/m²
Installation: 20 kg CO₂/m²
Operational: -155 kg CO₂/year/m²
End-of-Life: 50 kg CO₂/m²
Total Over 25 Years: $150 + 20 + (-155 \times 25) + 50 = -3,655$ kg CO₂/m²



Carbon Savings: $-1,740 - (-3,655) = 1,915 \text{ kg CO}_2/\text{m}^2$ over 25 years (110.1% additional reduction)

4.3.1.10 Daylight Louvers vs. Conventional Shading Devices

Conventional Shading Devices:

Manufacturing: 20 kg CO₂/unit

Installation: 3 kg CO₂/unit

Operational: 15 kg CO₂/year/unit

End-of-Life: 10 kg CO₂/unit

Total Over 25 Years: $20 + 3 + (15 \times 25) + 10 = 408 \text{ kg CO}_2/\text{unit}$

Daylight Louvers:

Manufacturing: 10 kg CO₂/unit

Installation: 2 kg CO₂/unit

Operational: 10 kg CO₂/year/unit

End-of-Life: 5 kg CO₂/unit

Total Over 25 Years: $10 + 2 + (10 \times 25) + 5 = 267 \text{ kg CO}_2/\text{unit}$

Carbon Savings: $408 - 267 = 141 \text{ kg CO}_2/\text{unit}$ over 25 years (34.6% reduction)

4.4 Case Studies LCA Results

The selection of the SUREFIT technologies in Finland, Greece, Portugal, Spain and UK building pilot are illustrated in Table 3.

SUREFIT Technologies	Finland	Greece	Portugal	Spain	UK
PV/T		X		X	
Bio Aerogel Insulation panel					X
PV Vacuum glazing		X	X	X	X
PV systems			X		X
Breathable Membrane		X		X	
PCM panel				X	



Evaporative coolers					X
Window heat recovery			X	X	X
Solar Assisted Heat Pump (SAHP)			X		X
Daylight louvers	X		X	X	
Smart Controls		X	X	X	X
Ground Source Heat Pump (GSHP)					X
Prefabricated panel		X		X	

Table 3 Selected SUREFIT technologies in each building pilot



5 Social Acceptance

To assess the social acceptability of the entire process, a comprehensive survey system has been developed. This system is designed to evaluate various stages of the technology installation.

Initial Survey

The first questionnaire focused on gathering feedback regarding the information provided about the project and the technologies planned for installation.

Mid-Installation Survey

The second questionnaire was aimed at evaluating the performance and outcomes of the installation process.

Both surveys have already been conducted. A final questionnaire will be administered once the homeowners have complete information on the savings and performance of the installation. This final survey will also capture the subjective perceptions of the indoor comfort within the houses.

Final Survey

The results of the final survey will be available towards the end of the project, after all installed technologies are operating for a long period of time in order for the building owners/occupants/tenants to have the maximum experience over the new technologies.

Technical survey for the stakeholders and visitors of the demo sites

This survey is presented in the ANNEX of this report and it will be distributed to the public that is to every stakeholder that will visit the demo sites or that will be informed in any way about the SUREFIT technologies that are installed in the various demo sites. The results of this survey will be available at the end of the project.

5.1 Initial Survey

Regarding the first form, the questions were the following:

- Q1. - Have you received information about the technologies to be installed in your building?
- Q2. - Was this information sufficiently clear and understandable?
- Q3. - From what you have understood, what are your expectations regarding the renovation?
- Q4. - Would you be willing to complete with your own means, actions not covered by SUREFIT?
- Q5. - Do you accept that during the renovation there may be inconveniences that alter your normal daily functioning?

Analysis

Question 1: Have you received information about the technologies to be installed in your building?

Response Analysis:



Yes: 80%

N/A: 20%

Most respondents (80%) confirmed that they received information about the technologies to be installed, indicating a strong initial communication effort. However, the 20% who did not receive any information is a concern and suggests a need for better outreach or communication strategies to ensure everyone is informed.

Question 2: Was this information sufficiently clear and understandable?

Response Analysis:

I have everything clear: 40%

I have understood all of it: 40%

N/A: 20%

Most respondents (80% combined) understood the information provided, though it is split evenly between those who felt they had complete clarity and those who were still missing some details. The 20% who did not answer or found the information unclear should be a focus for improvement to ensure that everyone has a clear understanding of the project.

Question 3: From what you have understood, what are your expectations regarding the renovation?

Response Analysis:

0.25 (low expectations): 40%

0.50 (moderate expectations): 40%

(Blank): 20%

Expectations are divided, with 40% having low and another 40% having moderate expectations. This mixed response could reflect uncertainty or varied understanding of the potential benefits of the renovation process. The 20% who did not provide an answer further highlights possible ambivalence or lack of engagement with the project.

Question 4: Would you be willing to complete with your own means, actions not covered by SUREFIT?

Response Analysis:

Yes: 50%

Depends: 20%

N/A: 20%

No: 10%

Half of the respondents are willing to contribute their own resources to cover actions not included by SUREFIT, indicating a strong commitment to the project's success. However, 30% of

respondents (those who answered "Depends" or "No") are hesitant, which suggests financial or motivational barriers that might need to be addressed.

Question 5: Do you accept that during the renovation there may be inconveniences that alter your normal daily functioning?

Response Analysis:

Yes: 80%

N/A: 20%

The majority (80%) of respondents are accepting of potential inconveniences during the renovation, demonstrating a high level of tolerance and support for the project. The 20% who did not respond affirmatively may need more information or reassurance to align their expectations with the project's demands.

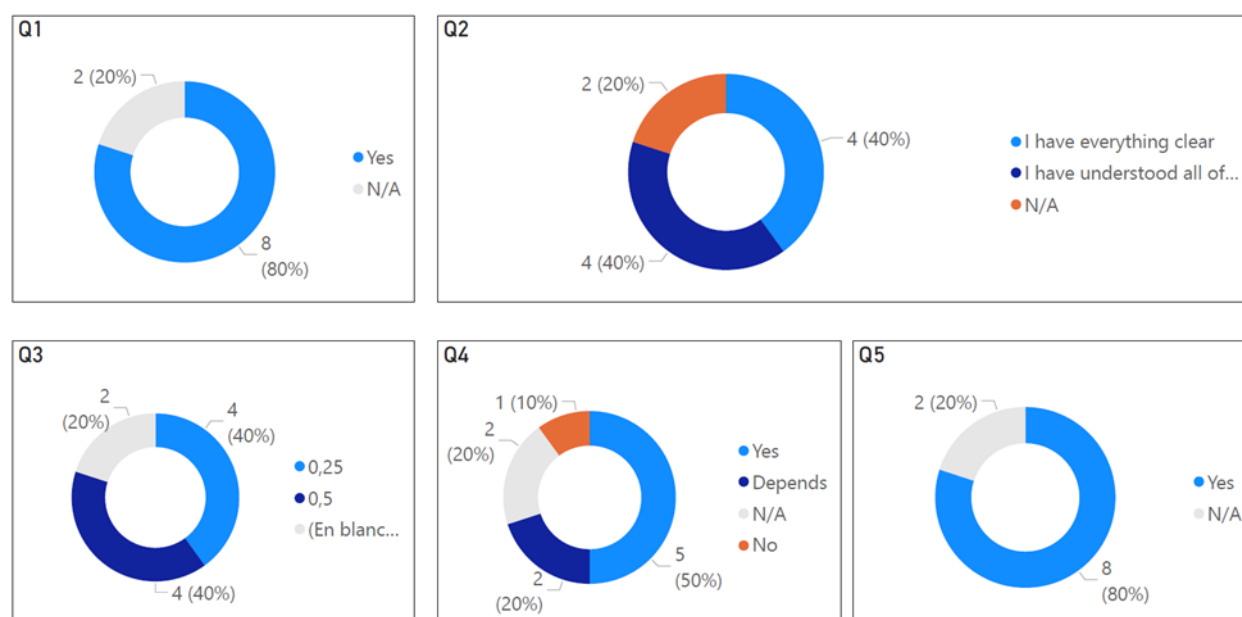


Figure 1 – Graphic analysis on the second survey

Geographical Analysis:

From the answers, it appears that responses vary by location, with the analysis showing responses from Greece, Portugal, Spain, the UK, and Finland. It would be beneficial to delve deeper into location-specific feedback to understand how local contexts might influence perceptions and expectations.

Overall Summary:

The survey indicated a generally positive reception to the information and process, with most respondents being informed, clear about the project, and willing to tolerate inconveniences. However, there are areas of concern, particularly with communication clarity, expectations, and



willingness to contribute additional resources. These areas need to be addressed to ensure full engagement and satisfaction across all respondents.

5.2 Mid-term Survey

Regarding the second form, the questions were the following:

Survey Questions:

- 1.- Overall Satisfaction: On a scale of 1 to 5, where 1 represents "Extremely dissatisfied" and 5 denotes "Extremely satisfied," please rate your overall satisfaction with the installation of the technologies.
2. - Disruptions during Installation: Have you experienced any notable inconvenience during the installation process of these technologies? Please describe any discomfort you may have experienced.
3. - Clarity of Information Provided: Was the information provided to you about the installation process clear and useful?
4. - Aesthetic Impact: From an aesthetic standpoint, how would you rate the final appearance of the installed technologies in your home? Do you believe the installation negatively impacted the aesthetics of your home?
5. - Additional Comments: Would you like to share any other important observations or additional comments regarding the installation of these energy efficiency technologies in your home?

This second survey primarily gathers qualitative data and subjective perceptions from the participants. Unlike quantitative surveys that rely on measurable, objective data, this survey focuses on the personal experiences, opinions, and perceptions of the respondents regarding the installation process and its impacts.

This qualitative approach allows for a deeper understanding of the participants' attitudes and feelings, providing rich, detailed insights into how the installation is perceived on a more personal level. However, the reliance on subjective data also brings certain challenges to the interpretation of the results. Subjective perceptions can vary widely among individuals, influenced by personal biases, expectations, and unique experiences. This variability means that the results may not be easily generalized across the entire participant group or to other similar projects.

Moreover, qualitative data often lacks the precision and consistency of quantitative data, making it more difficult to draw definitive conclusions or to compare results systematically. As a result, while the survey offers valuable insights into the human side of the installation process—highlighting areas of satisfaction or concern that might not be captured through quantitative measures—its findings must be interpreted with caution.

The implications of these subjective results are significant: they provide a nuanced view of the project's social acceptability but require careful consideration when being used to inform



broader project evaluations or decisions. It is important to complement these findings with additional quantitative data or further qualitative research to build a more comprehensive understanding of the overall impact of the SUREFIT technologies.

Summary of Findings:

The survey conducted to evaluate the post-installation experience of energy efficiency technologies reveals a generally positive reception among the respondents, although certain areas for improvement were highlighted. The overall satisfaction with the installation process is mostly positive, with respondents frequently selecting "Satisfied" or "Very satisfied" on a 5-point scale. This indicates that, overall, the technology installation met their expectations.

However, some respondents noted specific issues during the installation process, particularly regarding the technical knowledge of the installation team and the coordination among professionals. These concerns suggest that while the outcome was generally acceptable, the process could have been smoother and more efficient. There were also mixed reactions regarding the aesthetic impact of the installations. While some respondents were pleased with the final appearance, others felt that the installation detracted from the visual appeal of their homes, potentially clashing with the existing architecture or neighbourhood aesthetics.

Additional comments provided by the respondents shed light on broader concerns, such as the perceived maturity of the market in Spain and the need for better coordination and communication throughout the installation process. Some participants felt that the local market was not fully prepared for such advanced technological installations, which may have contributed to the issues encountered.

In conclusion, while the installation of these energy efficiency technologies was generally well-received, there are clear areas for improvement, particularly in the execution and coordination of the installation process and the consideration of aesthetic impacts. Addressing these concerns could enhance customer satisfaction in future projects, ensuring a smoother experience and a more positive overall outcome.

It is important to note that the analysis of the post-installation survey is based on a limited number of responses. This scarcity of data could significantly condition the results and their interpretation. With a small sample size, the findings may not fully represent the broader population's views or experiences.

The limited feedback can lead to an overemphasis on individual opinions, which might skew the overall analysis, either positively or negatively. Additionally, it reduces the reliability of drawing generalized conclusions about the installation process, satisfaction levels, and other critical factors like disruptions, clarity of information, and aesthetic impact.

Therefore, while the survey provides valuable insights, caution should be exercised in making broad assessments or decisions based solely on this data. To obtain a more accurate and



comprehensive understanding, it would be beneficial to gather more responses or consider supplementing this data with additional qualitative or quantitative research.

5.3 Conclusions

The surveys conducted so far provide valuable insights into the social acceptance of the installation process of the SUREFIT technologies. The results indicate a generally positive reception, with most respondents being informed about the project and willing to accept inconveniences during the renovation process. However, there are areas of concern, particularly regarding the clarity of information and the willingness of some participants to engage fully with the process.

The initial and mid-term surveys highlighted mixed expectations and varying levels of satisfaction among participants. While a significant portion of respondents understood the provided information and felt adequately informed, there was still a noticeable percentage that expressed uncertainties or found the information unclear. This gap suggests a need for enhanced communication strategies to ensure that all participants have a clear and comprehensive understanding of the project's scope and benefits.

Additionally, the willingness of participants to contribute their own resources to cover actions not included by SUREFIT varied, with only half of the respondents showing strong commitment. This variation underscores the importance of addressing potential financial or motivational barriers to maintain high engagement levels.

It is also important to note the scarcity of responses, which could condition the reliability and generalizability of the analysis. The limited feedback may overemphasize individual opinions, skewing the overall analysis either positively or negatively. This scarcity suggests that while the survey data provides valuable insights, caution should be exercised when drawing broad conclusions or making decisions based on this data alone. Gathering more responses or supplementing the data with additional research methods could offer a more comprehensive understanding.

The final survey, which will be administered once the installation is fully operational, will be crucial in capturing the complete picture of the project's impact, including energy savings and the subjective perception of indoor comfort. This survey will provide an opportunity to validate the initial findings and address any lingering concerns or issues identified in the earlier stages. The results of this final survey will be instrumental in assessing the overall success of the project and ensuring that the technologies meet the expectations and needs of the building occupants

6 Conclusion

The SUREFIT project developed a number of novel technologies suited primarily for refurbishment of current building stock as well as new buildings. Technologies included Bio-aerogel Insulation Panels, PV Glazing Units, Prefabricated Insulation Panels, Phase Change Materials Panels, Solar Assisted Heat Pumps, Ground Source Heat Pumps, Evaporative Cooling Units, Window Heat Recovery Units, Solar PV/Thermal Panels, and Daylight Louvers. These could be installed individually or in a larger building refurbishment. These technologies significantly reduced carbon emissions and energy costs to the consumer.

For each of the technologies, Life Cycle Analysis was conducted and covered the entire life cycle of these technologies, including manufacturing, installation, operational use, and end-of-life stage. Comparisons of carbon emissions of these innovative technologies with those of conventional systems are presented, providing detailed evaluation of their environmental performance. The broader implications of adopting these technologies, including cost-effectiveness, ease of implementation, and potential barriers to social acceptance are presented. The methodology of the assessment is presented in detail.

The effectiveness of the technologies in carbon reduction over existing Technologies includes 34% for Bio-aerogel panels, 59% for PV Glazing units, 49% for Prefabricated insulated panels, 46% for PCM panels, 55% for solar assisted heat pump, 40% for ground source heat pump, 67% for widow heat recovery units, and 34% for daylight louvers.

To achieve the greatest improvement, these systems can be used in combinations to enhance the building system performance. The installation into the five distinct environments of the five test houses allowed assessment of suitable for wide areas of Europe. The evaluation results, product economics, and Life Cycle Analysis provides guidance of installation advantages for the technologies.

User surveys were completed, and results presented.

- The **initial and mid-term surveys** show generally positive feedback on the SUREFIT installation process:
 - **Communication:** 80% of participants felt informed, though 20% found the information unclear, indicating room for better communication.
 - **Expectations:** Responses were mixed, with 40% having low expectations and only half willing to contribute beyond the project.
 - **Acceptance of disruptions:** 80% of participants were willing to tolerate inconveniences, while some raised concerns about the installation process and aesthetics.
- The **final survey**, which will be conducted after the technologies are fully operational, will focus on energy savings and indoor comfort. This survey will be crucial in providing a complete assessment of the project's success and addressing any lingering concerns from the earlier stages.



APPENDIX

The following questionnaire has been created to be shared with the public and more specifically with every stakeholder that will visit the demo sites or will be in any way informed about the installation and operation of the SUREFIT technologies in the five demo sites. The results will be available at the end of the project, i.e. in M54.



We are committed to ensuring that every visit to our DEMO sites is a valuable and enriching experience. To help us understand your thoughts and improve our technologies, we kindly ask you to participate in a brief questionnaire. Your feedback is invaluable to us, providing insight into what we are doing well and where we can enhance our research. Please take a few moments to share your honest opinions about your recent visit. Thank you for your time and input!

For each statement, please indicate your level of agreement or disagreement by selecting: (1 being not important at all, 5 being extremely important).

1. How important is it to you the have installed the prefabricated panel (specially in hot weather) protecting the house from overheating and keep it cooler?

1	2	3	4	5
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2. Did you already notice any difference on interior's temperature, in the good way?

1	2	3	4	5
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3. Based on the solar energy technology you have just seen, how interested are you in adopting a system that combines both electricity and thermal energy production in your home or business?

1	2	3	4	5
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4. Based on what you saw, how beneficial do you believe hybrid PV/T technology would be in reducing your energy bills?

1	2	3	4	5
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5. Based on the technology you have just seen; how important would you say energy efficiency is in your own choice of cooling technology?

1	2	3	4	5
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The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 894511.



6. Based on the PCM passive cooling technology you just saw, how interested are you in a cooling system that operates without electricity during the day?

1	2	3	4	5
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7. Based on the PV Vacuum glazing technology you have just seen, how interested are you in adopting a system that combines both renewable electricity generation and thermal insulation in your home or business?

1	2	3	4	5
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8. Based on what you saw, how beneficial do you believe PV Vacuum glazing technology would be in reducing the summer overheating?

1	2	3	4	5
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Applicable only to Finland, Portugal, Spain:

9. How interested are you in a passive daylight control system without wasting extra power for cooling but protecting the room from overheating and still allows daylight to come in, so that you don't need any electric lighting during sunshine hours?

1	2	3	4	5
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10. How important is it to you (especially in summer) to have a view through the window and simultaneously protecting the room from overheating?

1	2	3	4	5
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The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 894511.