# The impact of retrofitting in southern European residential buildings with intermittent or continuous heating

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*Abstract: Renovating the existing building stock is important for the building sector to reach the carbon neutral level. However, in addition to evaluating energy conservation and emission reduction potential brought by renovation, it is also significant to pay much attention to the indoor climate change after retrofit since people spend approximately 90% of their time indoors.*

*This study aims at comparing building energy consumption and indoor climate after implementing several novel renovation technologies and their packages in southern European residential buildings through building-level simulations. The novel technologies include bio-aerogel thermal insulation, photovoltaic vacuum window, phase change material, insulating breath membrane, room specific air handling unit with heat recovery, photovoltaic/thermal system and solar assisted heat pump. Three representative residential buildings in different southern European countries were chosen as the demo buildings to implement energy renovation in this study. These existing demo building models were simulated with an intermittent or continuous heating schedule in IDA ICE and used as the reference cases for renovation technologies simulations. The novel renovation technologies were classified into the passive package, ventilation package and generation package, and then integrated into the building models to evaluate their impact on building energy consumption and indoor climate.*

*The novelty of this study is to assess energy consumption and indoor climate change brought by the combinations of retrofit technologies in different southern European countries. It also reveals the impact of intermittent or continuous heating schedules on the energy conservation potential of retrofit technologies.*

*The impact of retrofit technologies on building energy consumption and indoor climate is significantly affected by heating schedules. The energy consumption reduction acquired by thermal insulation improvement under intermittent heating schedules is much lower than that under continuous heating schedules in all demo buildings since thermal insulation improvement resulted in an indoor air temperature increase when intermittently heated. Besides, when the intermittent heating schedule was switched to the continuous heating schedule, although the absolute energy consumption reduction brought by generation technologies increased, the relative reduction in percentage was diminished due to the increased backup energy demand for space heating.*

*Keywords: Residential building, Energy renovation, Intermittent heating, Energy conservation, Indoor climate*

## 1. INTRODUCTION

The building sector is the largest single contributor to energy consumption and carbon emissions in the EU, which accounts for 40% of total energy consumption and 36% of greenhouse gas (GHG) emissions. Thus, buildings conserve a great potential for energy conservation and emission reduction. As the new buildings are commonly constructed based on the energy efficiency regulations and only account for around 1% of the EU building stock, it is more important to renovate the existing building stock, especially those built up without taking the energy efficiency as a priority (*EURIMA - New and Existing Buildings*, 2018). Therefore, the EU commission published its Renovation Wave Strategy to accelerate building sectors towards climate-neutral levels by 2050 (*Renovation Wave*, 2020).

Following the renovation wave, SUREFIT project aims at finding sustainable solutions for affordable retrofit of the EU residential buildings. A target of this project is to reduce heat loss of the building envelope and energy consumption of heating, cooling, ventilation and lighting, while increasing share of renewable energy in the building to achieve near zero energy consumption. To explain the sustainable retrofit solutions intuitively, several representative residential buildings in different countries were chosen as the demo buildings to implement different energy-saving measures, including bio-aerogel thermal insulation, photovoltaic vacuum window, phase change material, insulating breath membrane, room specific air handling unit with heat recovery, photovoltaic/thermal system and solar assisted heat pump.

Although the performance of these retrofit technologies has been proved in several studies (Jarimi *et al.*, 2020; Barreto *et al.*, 2022), according to the authors' best knowledge, scientific research which combines them in different packages to assess their building level performance is still unavailable. The study focuses on comparing the impact of the combination of retrofit technologies on building energy consumption and indoor climate in southern European countries (Greece, Portugal and Spain). Besides, based on the simulations with different heating schedules, this study can also present the impact of intermittent or continuous heating schedules on the energy conservation potential of renovation technologies.

## 2. METHODOLOGY

### 2.1. Simulation setup

The demo buildings were modelled and simulated in a dynamic simulation tool IDA ICE, which is commonly used in Nordic countries. The building models were built up according to input data from building owners and online database TABULA WebTool (*TABULA WebTool*, 2021) and simulated on an hourly timescale to obtain hourly energy demand and indoor climate profiles. These demo building models were used as the reference cases for retrofit technology simulation.

The SUREFIT retrofit technologies were classified into different retrofit packages including the passive package, consisting of bio-aerogel thermal insulation, PV vacuum window, and phase change material; the ventilation package, consisting of insulating breath membrane and room specific air handling unit with heat recovery (RAHU); the generation package, consisting of photovoltaic/thermal (PV/T) system and solar assisted heat pump (SAHP). As shown in Figure 1, they were integrated into the reference case models with intermittent or continuous heating and simulated separately by following the rule of starting from a single technology to all technologies in each package. Finally, the simulated final combinations contain all the technologies in the passive and ventilation package and either of the technologies included in the generation package.

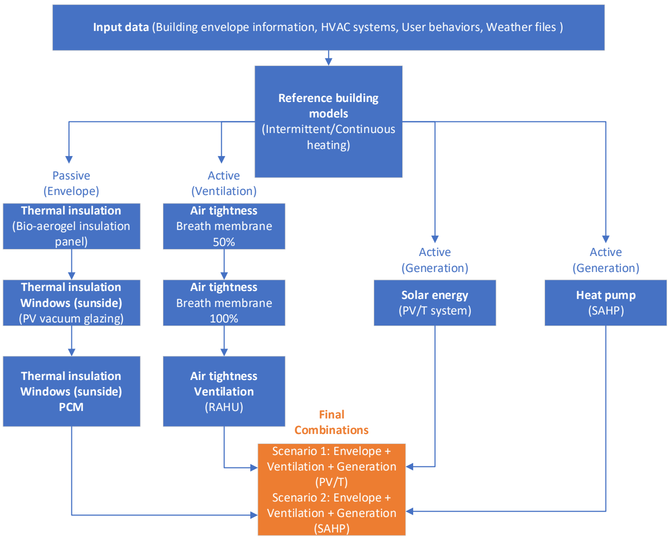

*Figure 1: Simulation of retrofit packages in IDA ICE.*

## 2.2. Demo building descriptions

The Greek demo located in Peristeri, Athens is a small apartment building constructed in 1980s. This apartment building consists of two apartments floors and a workshop. It is attached with two other buildings on the east and west sides. The apartment floors are heated with an oil boiler and water radiator system, and bedrooms and living rooms are equipped with electric air conditioners for cooling. Domestic hot water (DHW) is supplied by a solar thermal system.

The Portuguese demo building is a historic social house located in Lisbon. This demo building constructed in 1970s contains a ground floor as an apartment for one occupant and an upper floor as social space. All the living spaces are heated by portable electric heaters, while DHW heating is powered by a natural gas boiler.

The Spanish demo building is a terraced house in Valladolid. It consists of four apartments, and each apartment contains two residential floors and unheated basement floor. Each apartment is heated by an independent heating system, which are a mix of gas boilers and electric heaters.

*Table 1: Properties of building envelopes in the demo buildings before renovation.*

| Demo building | Greek apartment building | Portuguese social house | Spanish terraced house |
|---|---|---|---|
| U-values of envelope [W/m$^2$K] | | | |
| External wall | 0.7 | 2.4 | 1.7 |
| Roof | 3.9 | 3.8 | 1.6 |
| External floor | 3.6 | 1.0 | 2.9 |
| External door | 1.1 | 3.6/3.7/3.9 | 2.2 |
| Windows | 5.9/3.0 | 5.1 | 5.8/2.8 |
| Infiltration | | | |
| Air leakage rate, $n_{50}$ [ACH] | 6.7 | 6.7 | 6.7 |

*Table 2: Parameters of HVAC systems in the demo buildings before renovation.*

| Demo building | Greek apartment building | Portuguese social house | Spanish terraced house |
|---|---|---|---|
| Ventilation system | Natural ventilation | Natural ventilation | Natural ventilation |
| Space heating system | Oil boiler and water radiators | Portable electric heaters | Gas boiler and water radiators/Electric heaters |
| Maximum heating capacity of boiler [kW] | 65 | - | 65 |
| Efficiency of boiler [%] | 81 | - | 81 |
| Power of electric heater [kW] | - | - | |
| Setpoint, living spaces [°C] | 20 | 20 | 18-20 |
| Setpoint, other rooms[°C] | 20 | 20 | 18-20 |
| Design temperature of water radiators [°C/°C] | 90/60 | - | 70/40 |
| Heating design outdoor temperature [°C] | 1.8 | 4.9 | -4.1 |
| Cooling system | Split cooling units | No | No |
| Cooling capacity [kW] | 2.6/7.0 | - | - |
| Coefficient of performance | 3.1/5.6/6.1 | - | - |
| Setpoint [°C] | 25 | - | - |
| DHW | Solar collector and boiler | Gas heater | Gas boiler |
| Heating capacity [kW] | 65.0 | 19.2 | 65.0 |
| Efficiency [%] | 81 | 90 | 81 |
| Cold city water temperature [°C] | 15 | 15 | 12 |
| DHW outlet temperature [°C] | 55 | 45 | 55 |
| DHW use [L/day/person] | 50 | 100 | 26 |
| DHW recirculation loss [W/m$^2$] | 0.5 | - | - |

Table 1 and Table 2 show the properties of the building envelope and parameters of HVAC systems in each demo building before renovation. Most of the input data were provided by building owners, while the left unknown data were defined based on literature or TABULA WebTool. As field tests of airtightness were not implemented in these demo buildings, the air leakage rate at 50 Pa pressure difference used for simulation is an assumed value based on typical airtightness of residential buildings in southern European countries (e.g., Spain) (Feijó-Muñoz *et al.*, 2019).

## 2.3. Heating schedules

In this study, the building level simulations were implemented with both intermittent and continuous heating schedules. The intermittent heating schedules used for simulation were defined based on the occupant's feedback to reflect energy consumption level in the existing demo buildings, while the same continuous heating schedule was applicable for all demo buildings (see Table 3).

*Table 3: Intermittent and continuous heating schedule in the different demo buildings.*

| Demo site | Heated space | Intermittent heating schedule | Continuous heating schedule |
|---|---|---|---|
| Greek apartment building | The whole apartment area | From 1 Nov to 31 Mar, 20 °C [7-9, 19-22] | From 1 Sep to 31 May, 20 °C |
| Portuguese social house | All living spaces | From 1 Dec to 28 Feb, Weekdays: 20 °C [7-8, 15-23], Weekends & Holidays: 20 °C [8-23] | |
| Spanish terraced house | Ground floor | All year round, 20 °C [14-23], 17 °C otherwise | |
| | Top floor | All year round, 18 °C [14-23], 17 °C otherwise | |
| | Attic | From 1 Oct to 30 Apr, 20 °C [14-23] | |

## 2.4. Retrofit packages

*Passive package*

The passive package includes three technologies: bio-aerogel thermal insulation, PV vacuum glazing window and phase change material (PCM). Bio-aerogel thermal insulation is an environmentally friendly insulating material that is made of starch-based aerogel. It was made into a prefabricated panel installed on the outside or inside of the external walls and roofs in the demo buildings. PV vacuum window is a daylight-management apparatus with photovoltaic solar cells embedded in a window (Jarimi *et al.*, 2020). It can not only generate electricity during the daytime but also decrease heat transfer through windows due to its low U-value. To maximize the electricity generation of PV vacuum windows, they were installed on the south façade of the demo buildings. PCM is a substance that releases/absorbs sufficient energy at the phase transition between solid and liquid to provide useful heat/cooling. PCM product S21, a salt hydrate, was chosen and treated as an independent PCM layer installed under the ceiling of the demo buildings. The melting process starts at 18 °C, reaches its peak at 27 °C, and ends at 36 °C (PCM Products, 2021). Table 4 shows more detailed parameters of these retrofit technologies.

*Table 4: Parameters of retrofit technologies in the passive package.*

| Retrofit technology | Parameters |
|---|---|
| Bio-aerogel thermal insulation | Thermal conductivity [W/mK]: 0.037, Density [kg/m$^3$]: 43, Specific heat [J/kgK]: 2260, Thickness of insulation panel [m]: 0.05 |
| PV vacuum window | Solar heat gain coefficient (SHGC): 0.42, Solar transmittance: 0.3, Visible transmittance: 0.65, U-value of glazing [W/m$^2$K]: 0.6, Efficiency of electricity generation [%]: 3.5, Area of PV vacuum windows [m$^2$]: 11.2 (Greece), 1.1 (Portugal), 19.6 (Spain) |
| PCM Product S21 | Layer density (solid) [kg/m$^3$]: 1100, Layer specific heat (solid) [J/kgK]: 2300, Layer heat conductivity (solid) [W/mK]: 0.22, layer specific heat (liquid) [J/kgK]: 2300, Layer heat conductivity (liquid) [W/mK]: 0.22, Specific heat during reversing [J/kgK]: 300 |

*Ventilation package*

The ventilation package consists of insulating breath membrane and room specific air handling unit with heat recovery (RAHU). Insulating breath membrane could be seen as a thermal insulating measure which can also improve the airtightness of a building after retrofit (WINCO technologies, 2021). The breath membrane layer was installed over the external walls and roofs of the demo buildings. Since the air leakage rate of demo houses after installing insulating breath membrane was unknown, two cases with different assumed air leakage rates were simulated in this study: 50% airtightness improvement (the average value of the infiltration rate of the existing building and the tested air leakage rate of insulating breath membrane) and 100% airtightness improvement (the tested air leakage rate of insulating breath membrane). RAHU is an independent mechanical ventilation device installed above the windows, consisting of heat pipes and fans (Barreto *et al.*, 2022). All rooms with windows except kitchens and bathrooms in the demo buildings were equipped with RAHU, and their ventilation rates were defined based on the European standard for ventilation requirements. The efficiency of heat recovery depends on the airflow rate of ventilation systems. Detailed parameters of insulating breath membrane and RAHU are shown in Table 5.

*Table 5: Parameters of retrofit technologies in the ventilation package.*

| Retrofit technology | Parameters |
|---|---|
| Insulating breath membrane | Thermal conductivity [W/mK]: 0.029, Density [kg/m$^3$]: 96.15, Specific heat [J/kgK]: 2260, Thickness of insulating breath membrane [m]: 0.026, Airtightness (50% improvement) at 50 Pa [ACH]: 3.4, Airtightness (100% improvement) at 50 Pa [ACH]: 0.07 (Greece), 0.15 (Portugal), 0.11 (Spain) |
| RAHU | Supply & Exhaust airflow rate [L/s]: Greece: Living room: 15/14 Bedroom: 8/7/4, Portugal: Bedroom: 7 Social space: 24, Spain: Living room: 8 Bedroom: 5, Efficiency of heat recovery: Greece: Living room: 0.64/0.66 Bedroom: 0.76, Portugal: Bedroom: 0.76 Social space: 0.59, Spain: Living room: 0.76 Bedroom: 0.76 |

*Generation package*

The generation package includes two technologies: photovoltaic/thermal (PV/T) system and solar assisted heat pump (SAHP). PV/T system can convert solar radiation into usable thermal and electrical energy (Das, Kalita and Roy, 2018). As the most important component, the PV/T panel combines photovoltaic solar cells with a solar thermal collector. In this study, to maximize the energy return within limited installation space, the maximum available area for PV/T panel installation was used in the simulation to reduce the purchased energy as much as possible. Besides, the appropriate size of the water tank and backup heater were defined according to the heating capacity. SAHP is a heat pump in which solar collectors act as the evaporator in a single integrated system (Huang and Chyng, 2001). The solar collector operates more like an ambient heat exchanger than a solar thermal collector because it also transfers heat from ambient air through convection. It was placed on the roof of demo buildings to maximize the utilization of solar radiation. In order to cover as much heating demand as possible, the SAHP with maximum thermal generation capacity and the largest available water tank was tested in the simulations. Table 6 presents the parameters of the PV/T system and SAHP in different demo buildings.

*Table 6: Parameters of retrofit technologies in the generation package.*

| Retrofit technology | Parameters |
|---|---|
| PV/T system | Conversion factor of solar thermal: 0.486, Loss coefficient $a_1$ [W/m$^2$K]: 4.028, Loss coefficient $a_2$ [W/m$^2$K]: 0.067, Electricity generation efficiency: 0.13, Area of PV/T panel [m$^2$]: 26 (Greece), 24 (Portugal), 10 (Spain), Volume of hot water tank [m$^3$]: 1 (Greece), 1.4 (Portugal), 1 (Spain) |
| SAHP | Total heating capacity [kW]: 11, COP: 4, Dimension of each solar collector panel [m]: 2.1×0.81, Panel number: 4, Conversion factor $\eta_0$: 0.7, Loss coefficient $a_1$ [W/m$^2$K]: 4, Loss coefficient $a_2$ [W/m$^2$K]: 0.005 |

## 3. SIMULATED ENERGY CONSUMPTION AND INDOOR CLIMATE

### 3.1. Greek apartment building

Table 7 presents the breakdown of purchased energy, indoor temperature, and $CO_2$ concentration in the Greek apartment building before and after renovation when it was intermittently heated. Regarding the passive package, bio-aerogel thermal insulation, PV vacuum window and PCM brought 16%, 7% and 2% reduction in total purchased energy, respectively. In terms of the ventilation package, installing insulating breath membrane over the building envelopes reduced the total purchased energy by 15% when 50% airtightness improvement was assumed and 16% when 100% airtightness improvement was assumed. As there was only 1% difference between two cases, increasing airtightness had only a minimal effect on energy, implying that the main energy efficiency impact came from the thermal insulation improvement. The installation of RAHU increased the space heating demand, which led to 7% increase in total purchased energy, while it also brought the $CO_2$ concentration, which has increased significantly due to the airtightness improvement, back to below 1200 ppm again. Replacing the existing heating system with PV/T system or SAHP could reduce the total purchased energy by 24% or 38%. The final combination including PV/T system conserved a larger energy saving potential, which reduced the total purchased energy by 49%, than the final combination including SAHP, which reduced the total purchased energy by 46%.

*Table 7: Simulated energy consumption and indoor climate in the intermittently heated Greek apartment building.*

| | Energy consumption | | | Indoor climate | | | | |
|---|---|---|---|---|---|---|---|---|
| | Fuel [kWh/m²] | Elec [kWh/m²] | Total [kWh/m²] | T < 20 °C [%] | T > 25 °C [%] | T_max [°C] | $CO_2$ < 1200 [%] | $CO_2$ < 1800 [%] |
| Ref | 36.8 | 14.8 | 51.6 | 44.2 | 20.7 | 28.7 | 20.3 | 79.6 |
| Ins | 30.6 | 13.0 | 43.6 | 40.2 | 19.8 | 27.8 | 20.6 | 79.9 |
| Ins+Win | 27.9 | 11.7 | 39.6 | 34.3 | 24.4 | 28.6 | 20.8 | 80.8 |
| Ins+Win+PCM | 27.2 | 11.5 | 38.7 | 34.3 | 24.6 | 28.6 | 20.7 | 80.6 |
| Mem 50% | 30.9 | 13.1 | 44.0 | 40.0 | 19.9 | 27.8 | 12.8 | 66.4 |
| Mem 100% | 30.2 | 13.1 | 43.3 | 39.2 | 22.0 | 27.8 | 8.4 | 46.2 |
| RAHU | 32.1 | 14.6 | 46.7 | 42.5 | 19.5 | 28.2 | 100.0 | 100.0 |
| PV/T | 29.6 | 9.4 | 39.0 | 44.1 | 20.7 | 28.7 | 20.2 | 79.6 |
| SAHP | 0.0 | 32.0 | 32.0 | 44.2 | 20.7 | 28.7 | 20.3 | 79.6 |
| Pas+Ven+PV/T | 17.7 | 8.4 | 26.1 | 33.5 | 25.1 | 28.7 | 100.0 | 100.0 |
| Pas+Ven+SAHP | 0.0 | 27.8 | 27.8 | 33.2 | 25.1 | 28.7 | 100.0 | 100.0 |

***Ref**: Reference case before renovation; **Ins**: Bio-aerogel thermal insulation; **Win**: PV vacuum window; **Mem**: Insulating breath membrane; **RAHU**: Room specific air handling unit with heat recovery; **PV/T**: Photovoltaic/Thermal system; **SAHP**: Solar assisted heat pump; **Pas**: All the technologies included in the passive package; **Ven**: All the technologies included in the ventilation package; **T < 20 °C/T > 25 °C**: Proportion of time indoor temperature is lower than 20 °C or higher than 25 °C; **T_max**: Maximum air temperature; **$CO_2$ < 1200/1800**: Proportion of time $CO_2$ concentration is lower than 1200 or 1800 ppm.

*Table 8: Simulated energy consumption and indoor climate in the continuously heated Greek apartment building.*

| | Energy consumption | | | Indoor climate | | | | |
|---|---|---|---|---|---|---|---|---|
| | Fuel [kWh/m²] | Elec [kWh/m²] | Total [kWh/m²] | T < 20 °C [%] | T > 25 °C [%] | T_max [°C] | $CO_2$ < 1200 [%] | $CO_2$ < 1800 [%] |
| Ref | 109.3 | 18.2 | 127.5 | 0.6 | 0.0 | 25.0 | 21.7 | 79.7 |
| Ins | 56.5 | 14.3 | 70.8 | 0.9 | 0.0 | 25.0 | 21.4 | 80.2 |
| Ins+Win | 46.6 | 13.4 | 60 | 0.1 | 0.0 | 25.0 | 23.9 | 81.9 |
| Ins+Win+PCM | 45.9 | 13.4 | 59.3 | 0.0 | 0.0 | 25.0 | 23.6 | 81.7 |
| Mem 50% | 57.3 | 14.4 | 71.7 | 0.6 | 0.0 | 25.0 | 13.3 | 67.2 |
| Mem 100% | 54.2 | 14.4 | 68.6 | 0.5 | 0.0 | 25.0 | 10.4 | 48.6 |
| RAHU | 64.8 | 16.3 | 81.1 | 0.5 | 0.0 | 25.0 | 100.0 | 100.0 |
| PV/T | 99.2 | 10 | 109.2 | 0.0 | 0.0 | 25.0 | 22.0 | 61.8 |
| SAHP | 61.7 | 38.2 | 99.9 | 0.6 | 0.0 | 25.0 | 21.7 | 79.5 |
| Pas+Ven+PV/T | 35.7 | 7.5 | 43.2 | 0.4 | 0.0 | 25.0 | 100.0 | 100.0 |
| Pas+Ven+SAHP | 13.1 | 31.3 | 44.4 | 0.4 | 0.0 | 25.0 | 100.0 | 100.0 |

Table 8 shows the simulated energy consumption and indoor climate when the demo building was continuously heated. Due to the increased heating demand when it was continuously heated, the demo building consumed more than double the purchased energy under the intermittent heating schedule. The total purchased energy was reduced by 44%, 9% and below 1% after retrofitting with bio-aerogel thermal insulation, PV vacuum window and PCM, respectively. Installing insulating breath membrane conserved similar energy saving potential as bio-aerogel thermal insulation, which reduced the purchased energy by 44% with 50% airtightness improvement and 46% with 100% airtightness improvement, while it had a negative impact on indoor air quality, which meant $CO_2$ concentration was above 1800 ppm for half of the year due to the improved airtightness. Thus, after installing insulating breath membrane, equipping the Greek demo building with RAHU could ensure the $CO_2$ concentration always lower than 1200 ppm at the cost of a 10% increase in purchased energy. As for the generation measures, installing SAHP had a larger impact on building energy consumption (14% reduction) than PV/T system (22% reduction). Finally, retrofitting with the final combination including PV/T system or SAHP led to 66% or 65% decrease in total purchased energy.

The technologies aiming at improving thermal insulation performance (e.g., bio-aerogel thermal insulation, insulating breath membrane) brought much higher energy saving potential when the intermittent heating schedule was switched to the continuous heating schedule. As shown in Table 7, when it was intermittently heated, around 44% of the year the indoor temperature was lower than 20 °C before renovation, while this proportion became much lower after retrofitting the building envelopes. It means that thermal insulation improvement led to the indoor temperature increase. However, when the building was continuously heated, the indoor temperature was kept at the similar level before and after renovation. In addition, if the intermittent heating schedule was switched to the continuous heating schedule, although the absolute energy consumption reduction value became larger, the relative energy conservation potential of generation measures in percentage would be reduced. The capacity of generation measures could not cover the increased heating demand due to the extended heating time. The backup heating demand increased dramatically to satisfy the heating demand. The share of backup energy in total energy consumption became much higher than that of the utilized energy from generation measures when the Greek apartment building was continuously heated.

### 3.2. Portuguese social house

Table 9 shows the simulated energy consumption and indoor climate when the Portuguese demo building was intermittently heated. The bio-aerogel thermal insulation is the most effective measure for energy conservation, which resulted in 41% reduction in total purchased energy, while the impact of PV vacuum window and PCM was quite limited, only reducing the purchased energy by below 1%. When the insulating breath membrane was installed over the external walls and roof, the purchased energy was reduced by 36% with 50% airtightness improvement and 37% with 100% airtightness improvement. However, the airtightness improvement also made the $CO_2$ concentration level increase dramatically. After installing RAHU, the $CO_2$ concentration was controlled back to below 1200 ppm all year round, while the purchased energy increased by 11%. As the electric heaters were used as the space heating measures in this demo house, SAHP only covered the heating demand for DHW, saving 8% of the purchased energy. Compared with SAHP, the PV/T system was a better option for energy conservation by reducing 19% of the purchased energy in this demo house since there were lots of spaces available for PV/T panels on the roof. Correspondingly, the purchased energy was reduced by 59% after retrofitting with the final combination including PV/T system, higher than 47% reduction achieved with the other scenario including SAHP.

*Table 9: Simulated energy consumption and indoor climate in the intermittently heated Portuguese social house.*

| | Energy consumption | | | Indoor climate | | | | |
|---|---|---|---|---|---|---|---|---|
| | Fuel [kWh/m$^2$] | Elec [kWh/m$^2$] | Total [kWh/m$^2$] | T < 20 °C [%] | T > 25 °C [%] | T_max [°C] | $CO_2$ < 1200 [%] | $CO_2$ < 1800 [%] |
| Ref | 18.3 | 97.1 | 115.4 | 49.0 | 7.1 | 27.9 | 34.2 | 72.5 |
| Ins | 18.3 | 49.5 | 67.8 | 33.5 | 2.7 | 26.3 | 38.5 | 75.5 |
| Ins+Win | 18.3 | 49.2 | 67.5 | 33.6 | 2.2 | 26.2 | 39.0 | 75.7 |
| Ins+Win+PCM | 18.3 | 48.7 | 67 | 33.9 | 0.0 | 25.7 | 42.2 | 76.2 |
| Mem 50% | 18.3 | 55.3 | 73.6 | 36.7 | 3.8 | 26.5 | 23.6 | 61.6 |
| Mem 100% | 18.3 | 54.3 | 72.6 | 36.9 | 3.9 | 26.5 | 16.3 | 33.6 |
| RAHU | 18.3 | 66.8 | 85.1 | 42.9 | 2.0 | 26.8 | 100.0 | 100.0 |
| PV/T | 4.5 | 88.5 | 93 | 49.2 | 7.0 | 27.9 | 34.2 | 72.3 |
| SAHP | 3.7 | 102 | 105.7 | 49.1 | 7.1 | 27.9 | 34.1 | 72.4 |
| Pas+Ven+PV/T | 4.5 | 43.1 | 47.6 | 38.6 | 0.2 | 26.0 | 100.0 | 100.0 |
| Pas+Ven+SAHP | 3.7 | 57 | 60.7 | 38.4 | 0.5 | 26.1 | 100.0 | 100.0 |

*Table 10: Simulated energy consumption and indoor climate in the continuously heated Portuguese social house.*

| | Energy consumption | | | Indoor climate | | | | |
|---|---|---|---|---|---|---|---|---|
| | Fuel [kWh/m$^2$] | Elec [kWh/m$^2$] | Total [kWh/m$^2$] | T < 20 °C [%] | T > 25 °C [%] | T_max [°C] | $CO_2$ < 1200 [%] | $CO_2$ < 1800 [%] |
| Ref | 18.3 | 210.8 | 229.1 | 0.0 | 7.1 | 27.9 | 35.5 | 73.3 |
| Ins | 18.3 | 66.6 | 84.9 | 0.0 | 2.7 | 26.3 | 39.5 | 75.8 |
| Ins+Win | 18.3 | 65.9 | 84.2 | 0.0 | 2.2 | 26.2 | 40.0 | 76.2 |
| Ins+Win+PCM | 18.3 | 65.9 | 84.2 | 0.0 | 0.0 | 25.7 | 43.2 | 76.9 |
| Mem 50% | 18.3 | 77.2 | 95.5 | 0.0 | 3.8 | 26.5 | 24.3 | 61.8 |
| Mem 100% | 18.3 | 75.1 | 93.4 | 0.0 | 3.9 | 26.5 | 16.3 | 32.6 |
| RAHU | 18.4 | 98 | 116.4 | 0.0 | 2.0 | 26.8 | 100.0 | 100.0 |
| PV/T | 4.5 | 189.8 | 194.3 | 0.0 | 7.0 | 27.9 | 35.4 | 73.3 |
| SAHP | 3.7 | 215.8 | 219.5 | 0.0 | 7.1 | 27.9 | 35.4 | 73.2 |
| Pas+Ven+PV/T | 4.6 | 53.8 | 58.4 | 0.0 | 0.2 | 26.0 | 100.0 | 100.0 |
| Pas+Ven+SAHP | 3.8 | 74.9 | 78.7 | 0.0 | 0.5 | 26.1 | 100.0 | 100.0 |

Table 10 presents the breakdown of purchased energy, indoor temperature, and $CO_2$ concentration in the Portuguese social house before and after renovation when it was continuously heated. The total purchased energy consumption before renovation doubled, and the indoor temperature was always above 20°C when the heating schedule was switched to the continuous heating schedule. Just covering the building envelopes with bio-aerogel thermal insulation resulted in 63% energy saving, compared to the negligible impact of PV vacuum window and PCM on energy consumption. Due to the excellent thermal and airtight properties, installation of insulating breath membrane led to 58-59% reduction in the total purchased energy and increased proportion (up to 67%) of the time $CO_2$ concentration was above 1800 ppm. Then, equipping the living spaces with RAHU guaranteed the $CO_2$ concentration lower than 1200 ppm, while increasing the purchased energy by 10%. Replacing the existing gas heater with PV/T system or SAHP could reduce the total purchased energy by 15% or 4%. When these technologies were combined for renovation, the purchased energy was reduced by 75% or 66% after retrofitting with the final combination including PV/T system or SAHP.

Similar to the situation in the Greek apartment building, the energy conservation potential of thermal insulation improvement became more significant if the intermittent heating schedule was switched to the continuous heating schedule in the Portuguese social house. The indoor temperature before and after renovation was kept at a similar level (see Table 10) when the demo building was continuously heated, while thermal insulation improvement by bio-aerogel thermal insulation, insulating breath membrane etc. resulted in a significant indoor temperature increase (see Table 9) when it was intermittently heated. It means that partial of the building efficiency achieved by thermal insulation was converted into the increased temperature level. However, the energy conservation potential of generation measures in percentage was reduced significantly when the intermittent heating schedule was switched to the continuous heating schedule. The space heating demand doubled due to the increased heating time. In this demo building, the capacity of SAHP could only cover DHW heating demand. The share of DHW heating in the total purchased energy decreased as the space heating demand increased, resulting in a corresponding decrease in the contribution of SAHP to energy conservations. For PV/T system, although the increased heating time had led to more utilization of electricity generated by PV/T panels, the share of increased electricity consumption for space heating in total energy consumption far exceeded that of the utilized solar energy.

## 3.3. Spanish terraced house

As shown in Table 11, the retrofitting technologies affected the purchased energy and indoor climate at different levels when the Spanish terraced house was intermittently heated. Regarding the passive package, bio-aerogel thermal insulation, the most effective measure for energy saving, reduced the purchased energy by 43%, while PV vacuum window and PCM only brought 5% and 1% reduction, respectively. In terms of the ventilation package, installing insulating breath membrane over building envelopes could reduce the total purchased energy by 35% when 50% airtightness improvement was assumed and 36% when 100% airtightness improvement was assumed. The installation of RAHU increased the electricity consumption and space heating demand, which led to 8% increase in total purchased energy, while it also ensured the $CO_2$ concentration was below 1200 ppm almost all year round. Replacing the existing heating system with PV/T system or SAHP could reduce the total purchased energy by 18% or 36%. The final combination including SAHP conserved a larger energy saving potential, which reduced the total purchased energy by 71%, compare with the final combination including PV/T system, saving the purchased energy by 66%.

*Table 11: Simulated energy consumption and indoor climate in the intermittently heated Spanish terraced house.*

| | Energy consumption | | | Indoor climate | | | | |
|---|---|---|---|---|---|---|---|---|
| | Fuel [kWh/m$^2$] | Elec [kWh/m$^2$] | Total [kWh/m$^2$] | T < 18 °C [%] | T > 25 °C [%] | T_max [°C] | $CO_2$ < 1200 [%] | $CO_2$ < 1800 [%] |
| Ref | 115.0 | 19.4 | 134.4 | 5.1 | 11.9 | 30.5 | 41.3 | 98.1 |
| Ins | 58.0 | 19.3 | 77.2 | 0.0 | 11.4 | 29.6 | 43.9 | 98.6 |
| Ins+Win | 51.1 | 18.2 | 69.3 | 0.0 | 10.1 | 29.1 | 44.6 | 98.8 |
| Ins+Win+PCM | 50.2 | 18.2 | 68.4 | 0.0 | 10.5 | 28.5 | 45.4 | 98.9 |
| Mem 50% | 68.1 | 19.3 | 87.4 | 4.6 | 12.4 | 29.9 | 35.8 | 97.9 |
| Mem 100% | 67.2 | 19.3 | 86.5 | 0.0 | 12.0 | 30.2 | 24.2 | 95.7 |
| RAHU | 77.5 | 19.8 | 97.3 | 0.2 | 9.9 | 30.2 | 99.5 | 100.0 |
| PV/T | 97.1 | 12.5 | 109.6 | 5.1 | 11.7 | 30.4 | 41.2 | 98.1 |
| SAHP | 45.6 | 39.8 | 85.4 | 5.1 | 11.8 | 30.4 | 41.2 | 98.1 |
| Pas+Ven+PV/T | 33.1 | 12.7 | 45.8 | 0.0 | 8.3 | 28.3 | 99.5 | 100.0 |
| Pas+Ven+SAHP | 5.9 | 33.3 | 39.2 | 0.0 | 8.3 | 28.3 | 99.5 | 100.0 |

*Table 12: Simulated energy consumption and indoor climate in the continuously heated Spanish terraced house.*

| | Energy consumption | | | Indoor climate | | | | |
|---|---|---|---|---|---|---|---|---|
| | Fuel [kWh/m$^2$] | Elec [kWh/m$^2$] | Total [kWh/m$^2$] | T < 20 °C [%] | T > 25 °C [%] | T_max [°C] | $CO_2$ < 1200 [%] | $CO_2$ < 1800 [%] |
| Ref | 145.5 | 19.4 | 164.9 | 0.1 | 9.9 | 30.5 | 43.8 | 98.2 |
| Ins | 72.2 | 19.3 | 91.5 | 0.0 | 9.3 | 29.6 | 47.0 | 98.8 |
| Ins+Win | 62.9 | 18.1 | 81 | 0.0 | 8.2 | 29.1 | 48.3 | 98.9 |
| Ins+Win+PCM | 62.1 | 18.1 | 80.2 | 0.0 | 8.4 | 28.5 | 49.4 | 99.0 |
| Mem 50% | 84.5 | 19.3 | 103.8 | 0.0 | 9.8 | 30.2 | 36.7 | 97.9 |
| Mem 100% | 83.6 | 19.3 | 102.9 | 0.0 | 9.9 | 30.2 | 24.5 | 96.5 |
| RAHU | 97.9 | 19.8 | 117.7 | 0.0 | 8.2 | 30.2 | 98.4 | 100.0 |
| PV/T | 128.6 | 12.4 | 141 | 0.2 | 9.9 | 30.4 | 43.9 | 98.2 |
| SAHP | 60.6 | 44.4 | 105 | 0.2 | 9.9 | 30.4 | 43.9 | 98.2 |
| Pas+Ven+PV/T | 45.6 | 12.7 | 58.3 | 0.0 | 6.7 | 28.4 | 98.4 | 100.0 |
| Pas+Ven+SAHP | 6.5 | 37.7 | 44.2 | 0.0 | 6.4 | 28.3 | 98.4 | 100.0 |

Table 12 shows the simulated building energy consumption and indoor climate before and after renovation when the heating schedule was switched to continuous heating. In terms of the passive package, the energy conservation potential brought by bio-aerogel thermal insulation, PV vacuum window and PCM was 45%, 6% and less than 1% reduction, respectively. As for the ventilation package, installing insulating breath membrane over building envelopes could reduce the total purchased energy by 37% when the airtightness was improved by 50% and 38% when the airtightness was improved by 100%. The installation of RAHU ensured $CO_2$ concentration below 1200 ppm almost year-round at the expense of increased electricity consumption and space heating demand, 9% increase in total purchased energy. The total purchased energy was reduced by 14% or 36% when the existing heating system was replaced with PV/T system or SAHP. The final combination including SAHP saved more energy, 73% reduction in total purchased energy, than the final combination including PV/T system, saving the purchased energy by 65%.

As the intermittent and continuous heating schedules applied in the Spanish terraced house were quite similar, the energy conservation potential of thermal insulation measures only increased by 1-2% when the intermittent heating schedule was switched to the continuous heating schedule. The space heating demand before renovation increased by 25%, which was much lower than that in other demo buildings, if the continuous heating schedule replaced the intermittent heating schedule. Thus, the energy-saving potential of generation technologies in the continuously heated Spanish demo building was only up to 2% lower than their energy conservation potential in the intermittently heated Spanish demo building.

## 4. CONCLUSION

The recommendation priority of renovation measures was concluded based on the simulation results under the same heating schedule. In terms of the passive package, insulating the external walls and roof with bio-aerogel is the most recommended measure for energy conservation, while the installation of PV vacuum windows and PCM only has a slighter impact on energy consumption (up to 10% reduction). As a passive technology included in the ventilation package, insulating breath membrane has a similar energy saving potential to bio-aerogel thermal insulation and a negative impact on indoor air quality due to the improved airtightness. Considering about the indoor air quality issue, it is necessary to install RAHU after renovating the building envelopes with insulating breath membrane. Regarding the generation measures, the energy saving potential of PV/T system and SAHP varied considerably across different southern European demo buildings, which was 14-24% and 4-38%, respectively. The choice of generation measure depends on the actual conditions of the demo buildings. Finally, the maximum energy saving with the final combinations was up to 66%, 75% and 73% in the Greek, Portuguese and Spanish demo buildings when continuously heated.

The energy conservation potential of retrofit technologies was effectively affected by the heating schedules applied in the demo buildings. Commonly, the building energy efficiency achieved with thermal insulation improvement measures (e.g., bio-aerogel thermal insulation, insulating breath membrane etc.) was diminished when the continuous heating schedule was switched to the intermittent heating schedule. When the demo buildings were continuously heated, most of time indoor temperature was basically maintained at heating setpoint before and after improving thermal insulation performance. However, when they were intermittently heated, considerable proportion of time indoor temperature was lower than the heating setpoint due to the short heating period before renovation. Thus, although thermal insulation was improved significantly after renovation, the heating system still works at a high power to approximate the heating setpoint which means the space heating demand was not reduced as much as that in the continuously heated building. In brief, partial of the energy conservation potential brought by thermal insulation improvement was sacrificed for the improved indoor air temperature.

If the intermittent heating schedule was switched to the continuous heating schedule, the absolute energy consumption reduction brought by generation technologies increased, while the relative energy conservation potential in percentage became lower. The space heating demand is much higher under a continuous heating schedule than that under an intermittent heating schedule. The higher the space heating heat demand the lower the proportion of demand covered by generation measures and higher the proportion of backup heating demand. The energy conservation potential of generation measures lowered down following the increased ratio of backup heating demand.

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