Sustainable retrofit solutions for southern European residential buildings

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Abstract: As the building sector is the largest single contributor for energy consumption and greenhouse gas (GHG) emissions in the EU, improving building energy efficiency plays a key role in achieving the ambitious goal of carbon neutrality. In addition to constructing new buildings with energy efficiency regulation, it is also important to renovate the existing building stock for lower energy consumption and GHG emissions.

This study aims at verifying the building level performance of several novel retrofit technologies and their combinations under southern European climate conditions. The novel retrofit 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 in IDA Indoor Climate and Energy simulation software (IDA ICE) and used as the reference cases for retrofit technologies simulations. The retrofit technologies were classified into the passive package, ventilation package and generation package, and then integrated into the building models to examine their impact on primary energy and CO_2 emissions. Finally, different final combinations of retrofit technologies were simulated to achieve the lowest building energy consumption and CO_2 emissions after renovation.

According to the simulation results, the novel retrofit technologies all have a certain impact on primary energy and CO_2 emissions, while the impact of the same technology varies significantly in different demo buildings based on building type, climate conditions, heating schedules, etc. Regarding the performance of the final combinations, the maximum primary energy reduction after renovation was 48%, 58% and 64% in the Greek, Portuguese and Spanish demo buildings, the corresponding CO_2 emissions reduction of which was 48%, 58% and 66%, respectively. The lower reduction in the Greek and Portuguese demo building was caused by their heating schedules since energy renovation led to indoor air temperature level increase when the demo buildings were intermittently heated.

Keywords: Residential building, Energy renovation, Primary energy, CO_2 emissions

1. INTRODUCTION

The building sector accounts for 40% of total energy consumption and 36% of GHG emissions in the EU. Thus, improving building energy efficiency plays a key role in achieving the ambitious goal of carbon neutrality. New buildings constructed according to energy efficiency regulations (e.g., the Energy Performance of Buildings Directives) only account for little more than 1% of the EU building stock per year, while a substantial percentage of existing EU buildings was built without considering the energy efficiency as a priority (*EURIMA - New and Existing Buildings*, 2018). Thus, it is more important to renovate the existing EU building stocks with low energy efficiency. However, the current renovation rate of existing buildings is only 1.2-1.4% per year which cannot ensure the EU building sector towards climate-neutral levels by 2050 (*A renovation wave*, 2021). Therefore, the EU commission published its Renovation Wave Strategy to accelerate the renovation steps.

Under the background of renovation wave, SUREFIT project funded by the EU commission is committed to finding sustainable solutions for affordable retrofit of 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. More specifically, the goal of SUREFIT project is to reach a 60% reduction in primary energy consumption and CO_2 emissions of the demo buildings by retrofitting with different renovation measures.

In this study, the impact of SUREFIT retrofit technologies on primary energy and CO_2 emissions was evaluated in three representative residential buildings in southern European countries (Greece, Portugal and Spain) through building level simulations. In addition, the final combinations of retrofit technologies were also simulated to examine the maximum energy conservation potential of the demo buildings after renovation.

2. RESEARCH METHODS

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 the floor plan of the demo buildings. The specific parameters of the building envelopes and energy systems were defined based on the input data from building owners and the online database TABULA WebTool (*TABULA WebTool*, 2021) in the user interface. The models were simulated on an hourly timescale to obtain hourly energy demand profiles and used as the reference cases for retrofit technology simulation.

The SUREFIT retrofit technologies were classified into different retrofit packages including the passive package, containing 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); generation package, including photovoltaic/thermal (PV/T) system and solar assisted heat pump (SAHP). As shown in Figure 1, they were integrated into the reference case models, 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 generation package.

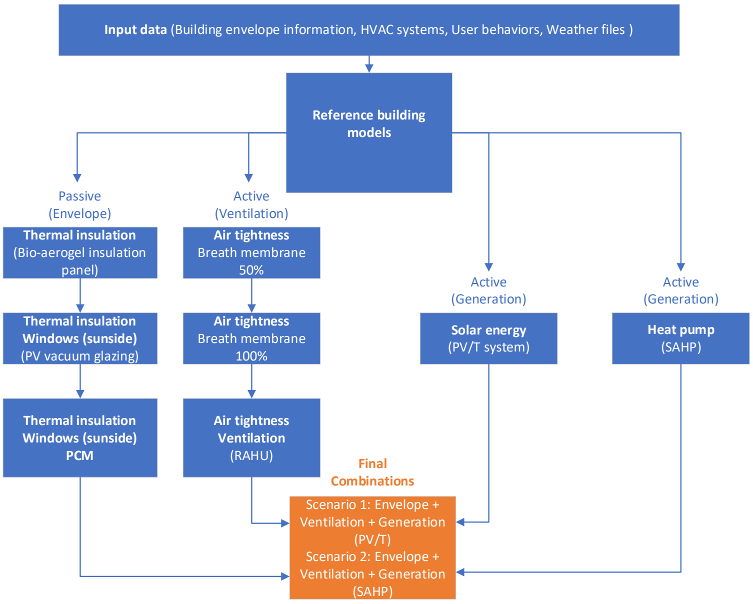

Figure 1 : Simulation of retrofit packages in IDA ICE.

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 demo building in Portugal 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. This demo house consists of four apartments. Each apartment contains two residential floors and unheated basement floor. It 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 shows 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 the building owners, while the left unknown data were defined based on literature or TABULA WebTool (*TABULA WebTool*, 2021). As the field tests of airtightness were not implemented in these demo buildings, air leakage rate at 50 Pa pressure difference used for simulation is an assumed value based on the typical airtightness of Spanish residential buildings (Feijó-Muñoz *et al.*, 2019).

As the energy demand for space heating accounts for most of the total energy consumption in residential buildings, it is important to define appropriate heating schedules to reflect energy consumption levels in the existing demo buildings. In southern European countries, residential buildings are commonly heated intermittently during the certain hours of the day. The apartments in the Greek demo building were heated two hours in the morning (7-9 am) and three hours in the evening (7-10 pm) from November to March. All the living spaces in the Portuguese social house were heated during 7-9 am, 7-10 pm from September to May. The Greek and Portuguese demo buildings were heated with a fixed heating setpoint (20 °C), while the Spanish demo building was heated using a varying setpoint, 18 or 20 °C during the day (2-11 pm) and 17 °C in the evening and morning.

2.3. Primary energy and carbon emissions

The energy generation mix varies in different southern European countries, which affects the corresponding primary and CO_2 emissions factors of energy generation. Table 3 shows the primary and CO_2 emissions factors of energy carriers in Greece, Portugal and Spain.

Table 3: Primary energy factors and CO_2 emissions factors in Greece, Portugal and Spain.

	Primary Energy Factors (kWh/kWh)			CO_2 Emissions Factors (kg-CO_2/MWh)		
	Natural gas	Oil	Electricity	Natural gas	Oil	Electricity
Greece	1.05	1.10	1.79	196	264	572
Portugal	1.00	1.00	1.49	204	267	227
Spain	1.07	-	1.51	199	-	190

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 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 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 which releases/absorbs sufficient energy at 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 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^2K]: 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 airtightness of 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 buildings 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 requirement. The efficiency of heat recovery depends on the air flow 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 water tank and back up 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 the 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 were tested in the simulations. Table 6 presents parameters of 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 at collector fluid temperature equal to ambient temperature a_1 [W/m^2K]: 4.028, Loss coefficient of a collector depends on the temperature a_2 [W/m^2K]: 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 η_0: 0.7, Loss coefficient at collector fluid temperature equal to ambient temperature a_1 [W/m^2K]: 4, Loss coefficient of a collector depends on the temperature a_2 [W/m^2K]: 0.005

3. SIMULATED ENERGY CONSUMPTION AND CO_2 EMISSIONS

3.1. Greek apartment building

Table 7 shows the purchased fuel, electricity, primary energy as well as CO_2 emissions in the Greek apartment building. Regarding the passive package, bio-aerogel thermal insulation brought 15% reduction in both primary energy use and CO_2 emissions since it affected the space heating demand significantly, while the installation of PV vacuum windows and PCM only reduced the primary energy by 8% and 2%, the corresponding CO_2 emissions reduction of which were 8% and 1%. As for the first step in the ventilation package, the installation of insulating breath membrane could result in 14% and 15% primary energy reduction with 50% and 100% airtightness improvement assumption. Considering the slight difference between two cases, increasing the airtightness had only a minimal effect on energy, implying that the main energy efficiency impact came from the added thermal insulation. RAHU has a negative effect on primary energy consumption and CO_2 emissions, increasing primary energy by 7% and CO_2 emissions by 8%. In terms of generation technologies, primary energy and CO_2 emissions after installing PV/T system was reduced by 26%, higher than 14% after installing SAHP. As SAHP consumed more electricity than PV/T system and CO_2 emissions factor is relatively high in Greece, the CO_2 emissions after retrofitting with PV/T system were even 1% higher than that before renovation. Thus, the final combination with PV/T system resulted in a higher primary energy and CO_2 emissions reduction (48%) in the Greek apartment building.

Table 7: Energy consumption and CO_2 emissions in the Greek apartment building before and after retrofitting.

		Fuel [kWh/m^2]	Electricity [kWh/m^2]	Primary energy [kWh/m^2]	CO_2 emissions [kg/m^2]
	Reference case	36.8	14.8	67.0	18.2
Passive package	Insulation	30.6	13	56.9	15.5
	Insulation + PV window	27.9	11.7	51.6	14.1
	Insulation + PV window + PCM	27.2	11.5	50.5	13.8
Ventilation package	Membrane (50% improvement)	30.9	13.1	57.4	15.7
	Membrane (100% improvement)	30.2	13.1	56.7	15.5
	RAHU	32.1	14.6	61.4	16.8
Generation package	PV/T system	29.6	9.4	49.4	13.2
	SAHP	0.0	32	57.3	18.3
Final combination	Passive + Ventilation + PV/T system	17.7	8.4	34.5	9.5
	Passive + Ventilation + SAHP	0.0	27.8	49.8	15.9

3.2. Portuguese social house

As shown in Table 8, the retrofit technologies changed energy consumption and CO_2 emissions at different levels in the Portuguese social house. For the passive package, bio-aerogel thermal insulation had the most significant impact on primary energy (44% reduction) and CO_2 emissions (43% reduction), while PV vacuum windows and PCM basically had no impact on energy conservation. Compared with bio-aerogel thermal insulation, the impact of insulating breath membrane was slightly lower, leading to 38% and 39% reduction in primary energy and 37% and 38% reduction in CO_2 emissions. After installing RAHU, primary energy consumption and CO_2 emissions increased by 11% due to the increased space heating demand. As PV/T system could produce electricity for electric heaters and thermal energy for DHW usage, while SAHP only covered DHW heating demand, PV/T system conserved a larger energy conservation potential (16% reduction) than SAHP (4% reduction). Therefore, compared with the final combination including SAHP, the final combination including PV/T system was more effective in the Portuguese social house, reducing primary energy and CO_2 emissions by 58%.

Table 8: Energy consumption and CO_2 emissions in the Portuguese social house before and after retrofitting.

		Fuel [kWh/m^2]	Electricity [kWh/m^2]	Primary energy [kWh/m^2]	CO_2 emissions [kg/m^2]
	Reference case	18.3	97.1	163.0	28.3
Passive package	Insulation	18.3	49.5	92.1	16.3
	Insulation + PV window	18.3	49.2	91.6	16.2
	Insulation + PV window + PCM	18.3	48.7	90.9	16.1
Ventilation package	Membrane (50% improvement)	18.3	55.3	100.7	17.7
	Membrane (100% improvement)	18.3	54.3	99.2	17.5
	RAHU	18.3	66.8	117.8	20.6
Generation package	PV/T system	4.5	88.5	136.4	23.3
	SAHP	3.7	102	155.7	26.6
Final combination	Passive + Ventilation + PV/T system	4.5	43.1	68.7	11.8
	Passive + Ventilation + SAHP	3.7	57	88.6	15.2

3.3. Spanish terraced house

Table 9 presents the purchased energy consumption, primary energy and CO_2 emissions before and after retrofitting the Spanish terraced house. In the passive package, bio-aerogel thermal insulation was the most effective technology, resulting in 40% and 43% reduction in primary energy and CO_2 emissions. Compared with bio-aerogel thermal insulation, the impact of PV vacuum windows and PCM was much lower, which only led to 6% and 1% reduction in primary energy. The installation of insulating breath membrane reduced the primary energy by 33% and 34% and CO_2 emissions by 35% and 36%, then to guarantee the indoor air quality, installing RAHU increased primary energy and CO_2 emissions by 8%. Regarding the generation measures, PV/T system and SAHP had a similar energy conservation potential, reducing primary energy by 25%, while the CO_2 emissions reduction with SAHP (35%) were higher than that with PV/T system (23%) since PV/T system consumed much more fuel for backup heating. Both final combination scenarios could reduce the primary energy and CO_2 emissions by over 60%. The primary energy and CO_2 emissions were reduced by 64% and 66% after retrofitting with the final combination including PV/T system, while the final combination including SAHP brought 61% primary energy reduction and 70% CO_2 emissions decrease in the Spanish terraced house.

Table 9: Energy consumption and CO_2 emissions in the Spanish terraced house before and after retrofitting.

		Fuel [kWh/m^2]	Electricity [kWh/m^2]	Primary energy [kWh/m^2]	CO_2 emissions [kg/m^2]
	Reference case	115.0	19.4	152.4	26.6
Passive package	Insulation	58.0	19.3	91.1	15.2
	Insulation + PV window	51.1	18.2	82.1	13.6
	Insulation + PV window + PCM	50.2	18.2	81.2	13.4
Ventilation package	Membrane (50% improvement)	68.1	19.3	102.0	17.2
	Membrane (100% improvement)	67.2	19.3	101.0	17.0
	RAHU	77.5	19.8	112.8	19.2
Generation package	PV/T system	97.2	6.6	113.9	20.6
	SAHP	49.1	40.0	112.9	17.4
Final combination	Passive + Ventilation + PV/T system	33.3	12.7	54.8	9.0
	Passive + Ventilation + SAHP	9.2	32.6	59.1	8.0

4. CONCLUSION

According to the building level simulations of retrofit technologies, they have an impact on primary energy and CO_2 emissions at different levels. Additional thermal insulation for external walls and roof was quite beneficial for reducing energy consumption for space heating. CO_2 emissions were reduced by 15-43% after adding bio-aerogel thermal insulation in all the demo buildings. The benefit acquired in different demo buildings varied depend on the ratio of heated spaces, heating schedules etc. The existing heating systems in the intermittently heated demo buildings could not ensure the heated spaces reach the heating setpoint during the limited daily heating time. Thus, even though the thermal insulation was improved significantly, the heating system still ran at a high power to reach the heating setpoint, which means the space heating demand did not decrease as much as expected. Compared with the thermal conditions before renovation, thermal insulation improvement resulted in a significant indoor air temperature increase. In comparison, PV vacuum windows and PCM provided smaller energy conservation and emission reduction potential (lower than 10%) in all the demo buildings.

In terms of the ventilation package, similar to bio-aerogel thermal insulation, insulating breath membrane was also effective for cutting down space heating demand, while the brought emission reduction level is lower (14-38%) due to the different thermal characteristics and panel thickness. Comparing 50% and 100% airtightness improvement cases, it can be concluded that the building energy efficiency achieved by installing insulating breath membrane mainly came from thermal insulation improvement instead of airtightness increase. Although installing RAHU had a negative impact on space heating demand, it is important to include it in the retrofitting scenario for a better indoor air quality if insulating breath membrane is installed.

Regarding the generation measures, due to the abundant solar energy in southern European countries, PV/T system provided more benefit for energy conservation than SAHP in all demo buildings. However, although installation of PV/T system resulted in lower primary energy consumption than SAHP in the Spanish demo buildings, installing SAHP led to lower CO_2 emissions because the CO_2 emissions factors of electricity is lower than that of natural gas in Spain.

Correspondingly, the final combination including passive package, ventilation package and PV/T system was a better option for energy conservation in southern European countries. As the building energy efficiency acquired by thermal insulation was effectively affected by intermittent heating schedules, retrofitting with the final combination including PV/T system only reduced the primary energy and CO_2 emissions by 48% in the Greek apartment building and 58% in the Portuguese social house. Both final combination scenarios led to similar primary energy and CO_2 emissions reduction in the Spanish terraced house, which were 64% primary energy and 66% CO_2 emissions reduction after retrofitting with the final combination including PV/T system and 61% primary energy and 70% CO_2 emissions reduction after retrofitting with the final combination including SAHP.

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