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CO_2 Emissions Reduction Potential with Novel Energy Renovation Technologies in English and Spanish Climate Conditions

TECHNICAL ARTICLE

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ABSTRACT

As the building sector acts as an important CO_2 emissions source, it is essential to renovate the existing building stock for carbon neutrality in the EU. The study reveals the effects of several novel renovation technologies on building energy consumption and CO_2 emissions through building simulations. An English semi-detached house and a Spanish terraced house were chosen as the simulated demo houses. Renovation technologies were divided into passive, ventilation, and generation packages and simulated by packages and final combinations. Insulating breath membrane and bio-aerogel thermal insulation are the most appropriate single technology for lowering CO_2 emissions for the English and Spanish demo houses, respectively. For generation technologies, solar assisted heat pump is a more recommended CO_2 emissions conservation technology than PVT system in both climate conditions. The demo houses' CO_2 emissions can be reduced maximally by over 70% after renovating with the final combination including solar assisted heat pump. The current economic feasibility of the novel technologies is limited by various issues, for example, manufacturing costs and energy prices. Nevertheless, considering most of the issues can be solved with time, they will be economically feasible renovation measures in the future.

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INTRODUCTION

Climate change mainly caused by greenhouse gas (GHG) emissions has become a worldwide hot topic over the last decades. In response to the climate challenge, the European Union (EU) sets a goal to be climate-neutral by 2050 (EC, 2010). The building sector shares 40% of the energy consumption and 36% of the GHG emissions from energy use in the EU (CITY MINDED, 2021). Thus, it is important to improve building energy efficiency for realizing carbon neutrality targets on time.

The latest proposal for the Energy Performance of Buildings Directive (EPBD) sets a target for achieving zero-emission new buildings by 2030 and zero-emission building stock by 2050 (*DIRECTIVE 2010/31/EU RECAST*, 2021). Over 94% of the existing buildings will still be in use by 2050 due to the low demolition rate. The majority of the existing buildings are old and energy inefficient. However, the current weighted energy renovation rate is only around 1% per year in the EU (Eurima, 2020). To achieve a climate-neutral Europe by 2050, it must achieve a minimum 3% renovation rate per year and an average energy efficiency improvement of 75% by 2030 (Eurima, 2021). Thus, to reach zero-emission building stock, it is necessary to speed up renovating the existing buildings.

Residential buildings account for the majority (75%) of the EU building stock, the proportion of which varies from 60% to 85% in different EU countries. Around 76% and 83% of the floor area in the UK and Spain was composed of residential buildings. In most EU countries, half of the residential stock was constructed before 1970 when the first thermal regulations were made. Nevertheless, the proportion (31%) of residential buildings built before 1970 in Spain is only half of that (62%) in the UK (*EU Buildings Factsheets*, 2016).

The old residential buildings were constructed without considering energy performance as a significant factor. They dominate the EU residential stock. Thus, the average EU residential end-use energy consumption level was relatively high at 184 kWh/m²a. The end-use energy consumption level (182 kWh/m²a) of the English residential stock is much higher than that (103 kWh/m²a) of the Spanish residential stock (*EU Buildings Factsheets*, 2016). The values further exceed the Nearly Zero Energy Building (NZEB) energy performance level for residential buildings in the corresponding countries (D'Agostino et al., 2021).

To reduce building energy consumption in the EU, many novel renovation technologies were developed, and their feasibility was verified in several studies. The most fundamental factor in lowering energy consumption is to reduce thermal resistance, particularly through improved insulation (Lakatos, 2018). Currently, aerogels are one of the most promising high-performance thermal insulation materials for building applications. It has a thermal conductivity of 2–2.5 times lower than that of conventional mineral wool (Baetens et al., 2011).

Building integrated photovoltaics (BIPV) windows, an integration of PV modules with traditional windows, is a promising method to lower cooling loads and to generate electricity in buildings. They have been proven to improve energy savings and daylight performance effectively (Miyazaki et al., 2005; Sun et al., 2018).

Phase change materials (PCM) can also be treated as novel building thermal insulation materials that appeared with the material advancement (Aditya et al., 2017). The focus of relevant researches has been on using PCM to achieve space thermal conditioning at a lower energy consumption rate (Li et al., 2015).

In mechanically ventilated buildings, heat recovery from air ventilation is the single most effective way to lower ventilation energy usage (Liu et al., 2010). Mechanical ventilation with heat recovery is commonly regarded as one key renovation measure for energy-efficient residential buildings in cold climates (Steimle F, 1992). According to a study aimed at typical Finnish residential apartments, a heat recovery system with 80% or 60% energy recovery efficiency can save up to 40% or 29% energy usage compared with a traditional exhaust ventilation system (Jokisalo et al., 2003).

In addition, solar-related renewable energy technologies possess a significant energy-saving potential in building renovations. They reduce externally supplied energy demand by utilizing solar energy through technologies, containing photovoltaic (PV) panels, solar thermal collectors, etc. Due to increased efficiency and lower purchase costs, PV panels have become a viable renewable technology for urban electricity generation (Lang et al., 2015). Optimized solar thermal systems can cover a significant proportion of domestic hot water (DHW) demand (Rad et al., 2013). Moreover, hybrid systems combining PV panels with solar thermal collectors and solar technologies with heat pumps may have a better energy generation efficiency than non-hybrid systems. They are more suitable for residential renovations (Felius et al., 2020). An overview of previous studies related to analyzed building renovation technologies is summarized in Table 1.

The impact of renovation technologies is significantly affected by climate conditions. Thermal insulation materials for building envelopes in cold and hot regions bring much better financial and ecological benefits than in moderate regions since heating or cooling energy demand shares a larger proportion of total building energy consumption (Aditya et al., 2017). As heat recovery technologies aim at reducing heating demand for supply air in the mechanical ventilation systems, their impact on energy conservation is more significant in cold climate conditions compared with other climate conditions (Fehrm et al., 2002; Mata et al., 2015). PV electricity output is lower in cold climate countries due to low solar radiation and also may be lowered throughout the winter if snow covers the panel (Adaramola and Vågnes, 2015).

In addition, there are also several relevant novel technologies, which have passed the laboratory verification stage and could confirm their viability at the building level. The 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. Although their impact has been studied in southern European climate conditions through simulations (Y. Wang et al., 2022), different climate conditions' influence on their renovation effects is remaining unknown. Besides, no previous study discussed the economic feasibility of these novel renovation technologies.

The study focuses on revealing and comparing the building-level impact of these novel renovation technologies and their combinations on energy consumption, CO_2 emissions and indoor climate in two different European climate conditions. The novelty of this study is to assess novel renovation technologies' effect and economic feasibility in the English and Spanish climate conditions. An English semi-detached house and a Spanish terraced house were selected as the simulated demo houses to compare building energy consumption and CO_2 emissions before and after renovations. The economic analysis of novel renovation technologies is also implemented to examine their feasibility in the demo houses. Thus, this research can act as a guideline for utilizing appropriate novel technologies in residential renovations in both climate conditions.

METHODOLOGY

Figure 1 shows an overview of the study's methodology. Firstly, the related input data, such as building and HVAC

RENOVATION CATEGORY	SPECIFIC RENOVATION TECHNOLOGIES	RELEVANT STUDIES
Building envelope renovation	Aerogel thermal insulation	Lakatos, 2018; Baetens et al., 2011
	Building integrated photovoltaics (BIPV) windows	Miyazaki et al., 2005; Sun et al., 2018
	Phase change materials (PCM)	Aditya et al., 2017; Li et al., 2015
Ventilation system renovation	Mechanical ventilation systems with heat recovery	Liu et al., 2010; Steimle F, 1992; Jokisalo et al., 2003
Energy system renovation	Photovoltaic (PV) panels	Lang et al., 2015
	Solar thermal systems	Rad et al., 2013
	Hybrid solar systems (Photovoltaic/Thermal (PV/T) panels, Solar assisted heat pump (SAHP))	Felius et al., 2020

Table 1 Summary of previous studies on analyzed building renovation technologies.

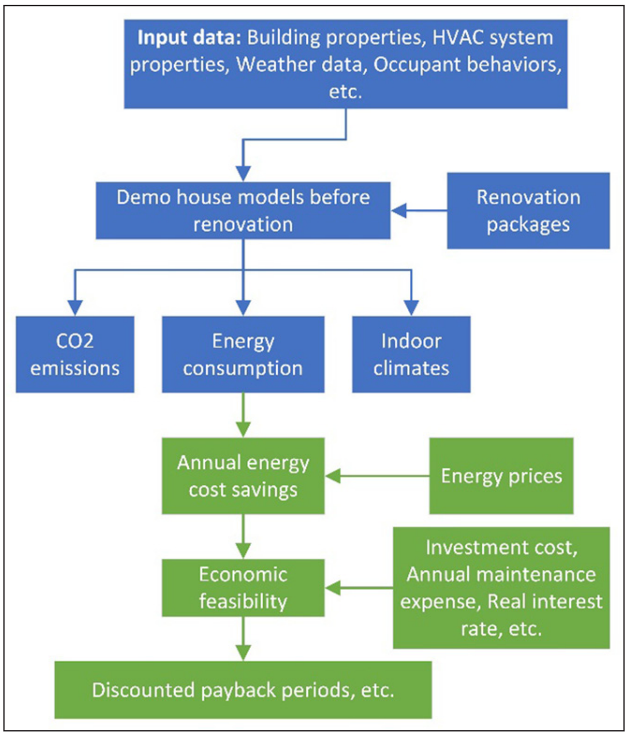

Figure 1 Flow chart of the study's methodology.

systems properties, were fed into the IDA ICE building models to simulate the demo houses' conditions before renovation. These demo house models were calibrated by using the measured data of energy consumption and indoor climate (Hirvonen et al., 2022). Then, the novel renovation technologies were integrated into the building models by packages to reveal their impact on building CO_2 emissions, energy consumption and indoor climate. In terms of economic analysis of building renovations, the exported energy consumption from simulations was used to calculate the annual energy cost savings. With such values and other parameters, including investment cost, maintenance expense, etc., some factors (e.g., discounted payback periods) were calculated in Excel to show building renovations' economic feasibility.

BUILDING DESCRIPTION

The study aims at analyzing two different demo houses, including a semi-detached house in Nottingham, UK and a terraced house in Valladolid, Spain. The English demo house was constructed in 1948. It comprises two residential floors and an attic floor above. The Spanish demo house consists of four apartments, constructed in the 1950s. Each apartment has two residential floors and an unheated basement floor.

Tables 2 and 3 show detailed building properties and HVAC system types and their properties in both demo houses, respectively. Most of these values are defined based on the design information, while the remaining data, unavailable in the design information, are set according to an online database (TABULA WebTool, 2015). The average infiltration air change rate of the English demo house has been defined as a fixed value instead of a wind-driven variable value according to the field measurement. The typical airtightness of Spanish residential buildings was applied in the simulation model of the Spanish demo house since the measured data was unavailable (Feijó-Muñoz et al., 2019).

DEMO HOUSE	ENGLISH SEMI-DETACHED HOUSE	SPANISH TERRACED HOUSE
Building properties		
Total floor area [m^2]	115.7	298.3
Heated floor area [m^2]	107.8	99.1
Model volume [m^3]	307.7	941.5
Ground area [m^2]	63.8	104
Envelope area [m^2]	259.7	607.3
Window/Envelope [%]	13.7	4.9
Average U-value [W/m^2K]	1.3	0.7
Envelope area per volume [m^2/m^3]	0.8	0.6
Envelope properties		
U-value of external wall [W/m^2K]	2.1	1.69
U-value of roof [W/m^2K]	0.22	1.64
U-value of external floor [W/m^2K]	0.85	2.9
U-value of external door [W/m^2K]	3.1	2.2
Windows		
U-value [W/m^2K]	2.4/2.5	2.8/5.7
Solar heat gain coefficient (SHGC)	0.76	0.76
Solar transmittance	0.7	0.7
Visible transmittance	0.81	0.81
Window blinds	–	–
External shading	–	–
Infiltration		
Air leakage rate, n_{50} [ACH]	16.1	6.7

Table 2 Building properties of the demo houses before renovation.

DEMO HOUSE	ENGLISH SEMI-DETACHED HOUSE	SPANISH TERRACED HOUSE
Ventilation	Mechanical exhaust ventilation for kitchen, bathroom and toilet; Natural ventilation for other spaces	Natural ventilation
Exhaust air flow rate [L/s]	Kitchen: 15, Bathroom: 10, Toilet: 3	–
Space heating	Natural gas boiler and water radiators for most spaces; Electric radiators for dining room and attic	Natural gas boiler and water radiators
Maximum capacity of boiler [kW]	24	84.4
Efficiency of boiler [%]	94	90
Heating setpoint [°C]	19.5	–
Heat distribution [°C/°C]	70/40	70/40
Design temperature [°C]	–3.2	–3.8
Domestic hot water	Electric water heater	Natural gas boiler
Efficiency of electric water heater [%]	85	90
Cold city water temperature [°C]	10	12
DHW outlet temperature [°C]	47	55
DHW use [L/day/person]	20	22

Table 3 Properties of HVAC systems in the demo houses before renovation.

COUNTRY SPECIFIC INPUT DATA

Weather conditions

The ASHRAE IWEC2 weather files for Nottingham, UK and Valladolid, Spain were applied in IDA ICE simulations. The weather files contain the data, including the hourly outdoor air temperature, relative humidity, wind speed and direction and direct and diffused radiation.

The hourly maximum and minimum outdoor temperatures are 30.4°C and –5.8°C, respectively, in Nottingham. In comparison, these two indexes are higher in Valladolid, which are 36.3°C and –4.3°C. The annual average outdoor temperature in Valladolid (12.3°C) is slightly higher than that (10.0°C) in Nottingham. In addition, the annual heating degree hours at an indoor temperature of 15.5°C are 1671°Ch in Nottingham and 1578°Ch in Valladolid, respectively.

As for solar radiation, the annual global solar radiation is 1250 kWh/m^2 in Nottingham and 2191 kWh/m^2 in Valladolid. The solar radiations in both two cities reach the maximum value in July, which is 180 kWh/m^2 in Nottingham and 294 kWh/m^2 in Valladolid, and then it drops to the bottom value in January (37 kWh/m^2 in Nottingham) or December (85 kWh/m^2 in Valladolid). Thus, a significant gap exists between solar radiation and space heating demand.

Primary energy and CO_2 emissions factors

In the study, the primary energy factors (PEFs) have been introduced to translate the energy demand of buildings into the primary energy demand. Similarly, CO_2 emissions factors can be used to calculate the building CO_2 emissions according to the simulated purchased energy. Table 4 shows the PEFs and CO_2 emissions factors of natural gas and electricity in the UK and Spain. The CO_2 emissions factor of electricity in the UK is much higher than that in Spain since it has a higher proportion of electricity generated by fossil fuels in the UK compared to Spain.

User behaviors

The usage profiles applied in the simulations were developed according to building occupants' feedback or prior experiences since user behaviors have a substantial

	ENERGY CARRIER	PRIMARY ENERGY FACTORS [kWh/kWh]	CO_2 EMISSIONS FACTORS [kg-CO_2/MWh]
UK	Natural gas	1.13	203
	Electricity	1.5	231
Spain	Natural gas	1.07	199
	Electricity	1.51	190

Table 4 Primary energy and CO_2 emissions factors in the UK (GOV.UK, 2020; BRE Group, 2019) and Spain (Tilastokeskus, 2021; Red Eléctrica DE España, 2021).

impact on building energy consumption and indoor environment.

There are three residents living in the English demo house, while each apartment in the Spanish demo house is occupied by two persons. Different occupancy schedules were defined for each type of room in both demo houses. In the English demo house, the annual electricity consumption of lighting and equipment was normalized to 2.2 kWh/m²a and 4.6 kWh/m²a based on the measured data. The rated input of lighting and equipment was estimated to be 2.0 kW/m² and 6.7 kW/m² in the Spanish demo house.

In both demo houses, the external doors are always closed, while the internal doors are open. As for window opening, an opening macro was customized based on ambient temperature, room temperature, occupancy schedule and indoor air quality.

According to occupants' feedback, different heating schedules were applied in different spaces of both demo houses. In the English semi-detached house, most of the living spaces except the kitchen and attic are continuously heated to 19.5°C, while the kitchen and attic are only heated when they are occupied. All the living spaces in the Spanish terraced house are continuously heated with different setpoints (18/20°C) during different time periods for each floor (Y. Wang et al., 2022).

NOVEL TECHNOLOGIES

The novel renovation technologies were categorized into three different renovation packages (see Figure 2): the passive, ventilation and generation packages. Each package was integrated into the demo house models and simulated separately. The simulation of renovation technologies in the same package followed the rule of progressing from one technology to all of them. Then, two final combination scenarios were also simulated to reveal the maximum building energy saving and CO_2 emissions reduction potential. The final combinations contain all the technologies in the passive and ventilation package and either of the technologies included in the generation package.

Passive package

The passive package includes bio-aerogel thermal insulation, PV vacuum window and phase change material (see Figure 2).

Bio-aerogel thermal insulation made of starch-based aerogel has a similar insulation performance to common thermal insulation material (e.g., mineral wool) while possessing the characteristics of non-toxicity and biodegradability (Nita et al., 2020). In the study, bio-aerogel thermal insulation was simulated as prefabricated panels installed on the outside of the building envelopes. Its detailed properties and the U-value of building envelopes after renovation are presented in Table 5.

PV vacuum window is a daylight-management device that has photovoltaic solar cells embedded between glazing (Jarimi et al., 2020). In addition to the electricity generation capacity, PV vacuum window has a low U-value, which decreases heat transfer through windows. In the study, only the windows on the south facades of both demo houses were replaced by PV vacuum windows. Table 5 shows more detailed properties of PV vacuum windows.

Phase change material (PCM) is a substance that releases or absorbs thermal energy at the solid-liquid phase transition to provide useful heat or cooling

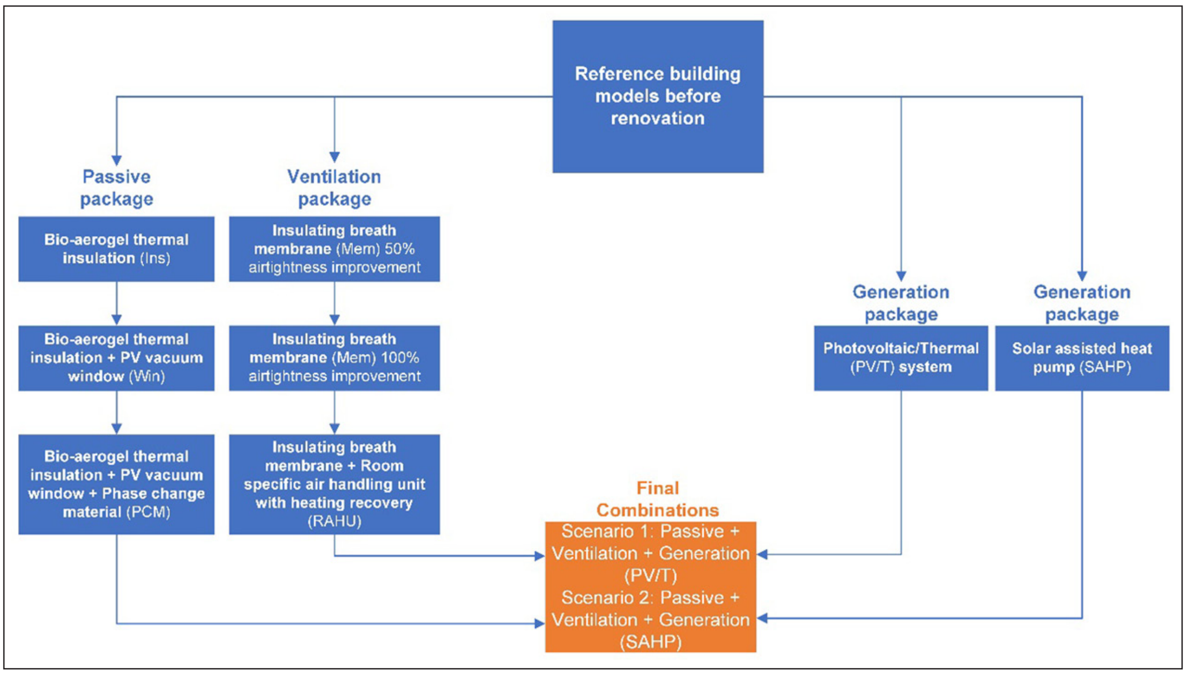

Figure 2 Simulation of renovation packages in IDA ICE.

(X. Wang et al., 2022). In the study, PCM product S21, a salt hydrate, was chosen and put as a separate layer underneath the ceiling of living spaces in the demo houses. Although the nominal melting temperature of S21 is 22°C, the actual melting process starts at 18°C, reaches its peak at 27°C, and ends at 36°C (Y. Wang et al., 2022). More detailed properties of PCM product S21 are shown in Table 5.

Ventilation package

The ventilation package comprises of insulating breath membrane and room specific air handling unit with heat recovery (RAHU).

Insulating breath membrane is another thermal insulating measure included in the study. In addition to its impact on the thermal insulation performance of building envelopes, it also helps to improve building airtightness (Wincotech, 2022). In the study, the insulating breath membrane was treated as an independent layer (26 mm) which covered all the external walls and roofs of the demo houses. As the measured building airtightness after renovating with insulating breath membrane is unavailable, two possible cases were assumed and simulated including the 50% and 100% airtightness improvement case. Table 6 presents detailed properties of insulating breath membrane and assumed building air leakage rate after renovation.

Room specific air handling unit with heat recovery (RAHU) is an independent mechanical ventilation apparatus installed above the window frames. It mainly comprises of heat pipes that utilize the extra heat of exhaust air to heat supply air through phase change

Properties of bio-aerogel thermal insulation panel		
Thermal conductivity [W/mK]: 0.024, Density [kg/m^3]: 43, Specific heat [J/kgK]: 2260, Thickness of insulation panel [m]: 0.05		
U-value of building envelope after renovation		
Demo house	English semi-detached house	Spanish terraced house
U-value of external wall [W/mK]	0.39	0.37
U-value of roof [W/mK]	0.15	0.37
Properties of 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		
Total area of PV vacuum windows in different demo houses		
Demo house	English semi-detached house	Spanish terraced house
Area of PV vacuum windows [m^2]	12.8	19.6
Properties of PCM product S21		
Layer thickness [mm]: 32, Number of temperature coordinates: 9, Number of partial enthalpies: 8, 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		

Table 5 Properties of technologies in the passive package.

Properties of insulating breath membrane		
Thermal conductivity [W/mK]: 0.029, Density [kg/m^3]: 96.15, Specific heat [J/kgK]: 2260		
U-value of building envelopes and air leakage rate after renovation		
Demo house	English semi-detached house	Spanish terraced house
U-value of external walls [W/mK]	0.73	0.67
U-value of roof [W/mK]	0.18	0.66
Air leakage rate (50% improvement) at 50 Pa [ACH]	8.1	3.4
Air leakage rate (100% improvement) at 50 Pa [ACH]	0.14	0.11
Ventilation rates of RAHU in different demos		
Demo house	English semi-detached house	Spanish terraced house
Supply & Exhaust airflow rate [L/s]	Living room: 8, Bedroom: 7/8	Living room: 8, Bedroom: 5

Table 6 Properties of technologies in the ventilation package.

of volatile liquid inside and fans aiming to promote air circulation (Barreto et al., 2022). In the study, all the living rooms and bedrooms in the demo houses were equipped with RAHUs. The specific ventilation rate in each demo (see Table 6) was defined based on the suggested ventilation rate from guidelines (Arisoy et al., 2021). The efficiency of heat recovery was 0.76 according to the suggested ventilation rate of the living room and bedroom.

Generation package

There are two different technologies, photovoltaic/thermal (PV/T) system and solar assisted heat pump (SAHP), in the generation package. As shown in Figure 2, to compare their building-level performance, they were integrated and simulated separately in the demo house models.

Photovoltaic/thermal (PV/T) system is a power generation technology that converts solar radiation into usable thermal and electrical energy (Das et al., 2018). The system mainly consists of PV/T panels, a hot water tank and a backup heater (see Figure 3). Due to the combination of electricity and heat generation within the same component, PV/T system could reach a higher overall efficiency than solar photovoltaic or solar thermal system alone. In the study, the PV/T system covered partial load of electricity consumption, DHW and space heating. The existing gas boilers were used as backup heaters. Table 7 shows detailed properties of the PV/T system.

Solar assisted heat pump (SAHP) is a type of heat pump the evaporator of which is connected to a solar thermal collector through a heat exchanger. The SAHP analyzed in the study is an indirect expansion SAHP system (see Figure 4) (Fan et al., 2021). Nevertheless, a mismatch exists between the time with sufficient solar radiation and the time when heating demand is needed. Thus, the solar collector operates more like an ambient heat exchanger which acquires thermal energy from the ambient air when solar radiation is unavailable. The SAHP was used for both space and DHW heating in both demo houses. The existing gas boilers were preserved as backup heaters. More detailed properties of the SAHP are presented in Table 7.

BUILDING-LEVEL SIMULATIONS

Simulation tool

The dynamic simulation software IDA ICE was used as the tool to model the demo houses and renovation technologies in the study. It is a framework that enables

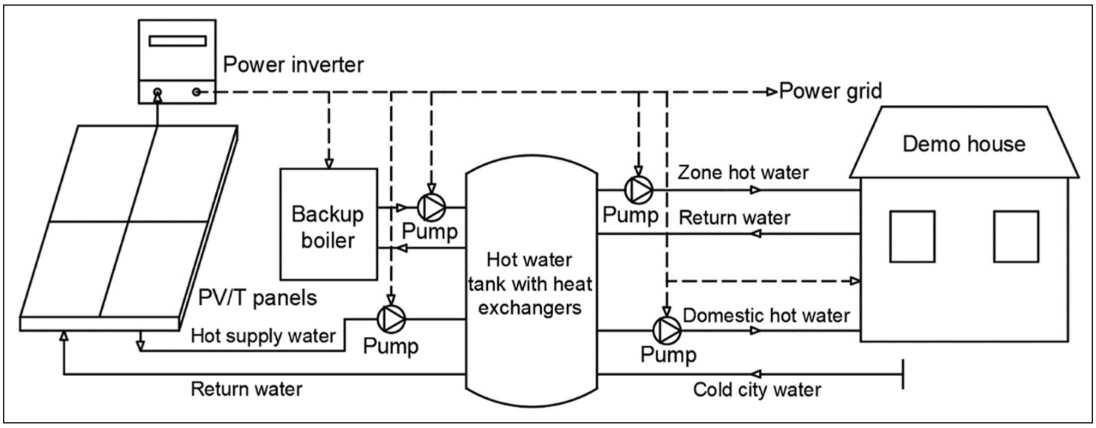

Figure 3 Schematic diagram of PVT system.

Properties of PV/T panel		
Conversion factor of solar thermal: 0.486, Loss coefficient at collector fluid temperature equal to ambient temperature a_1 [W/m²K]: 4.028, Loss coefficient of a collector depends on the temperature a_2 [W/m²K]: 0.067, Electricity generation efficiency [%]: 13		
Specific panel area and tank size		
Demo house	English semi-detached house	Spanish terraced house
PV/T panel area [m²]	14	20
Hot water tank size [m³]	0.8	2.0
Properties of SAHP		
Total heating capacity [kW]: 11, COP: 4, Hot water tank size [m³]: 0.42, 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/m²K]: 4, Loss coefficient of a collector depends on the temperature a_2 [W/m²K]: 0.005		

Table 7 Properties of technologies in the generation package.

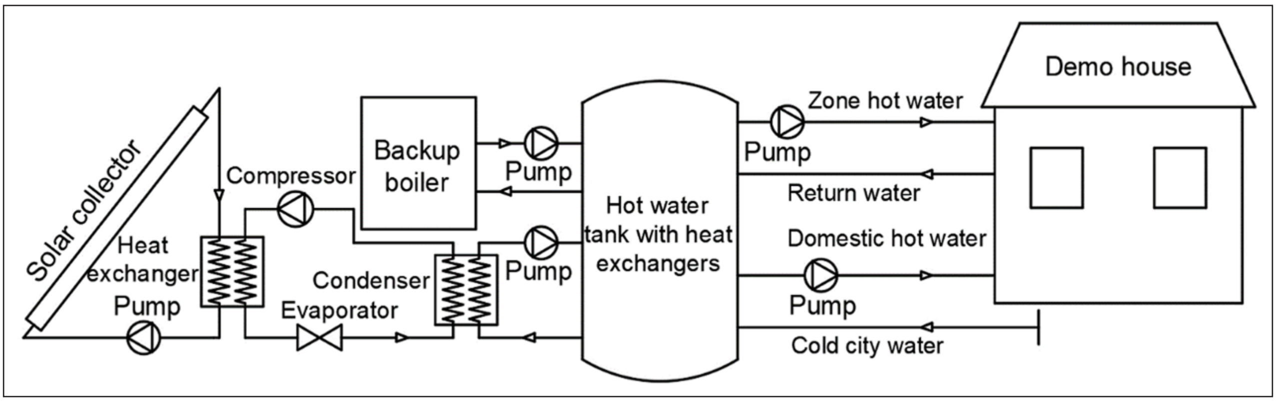

Figure 4 System diagram of indirect expansion SAHP.

the modeling of dynamic multi-zone simulations and building characteristics, such as geometry, structures and technical systems. The building, its systems and controllers can all be precisely modeled using IDA ICE to produce data in terms of building energy use, indoor air quality, and thermal comfort. It was validated against the EN 15255-2007 and EN 15265-2007 standards (EquaSimulation AB, 2010). Several researches have validated the simulation tool as well, which provides strong justification for using IDA ICE in the study (Bjorsell et al., 1999; Dimitruk et al., 2007).

Modelling of the novel technologies

The extensive simulation of novel renovation technologies is also supported by IDA ICE. The default standard models or customized models based on them were used to mimic these renovation technologies (Y. Wang et al., 2022). The simulated models were fed with the material or technical characteristics of each technology.

It is worth mentioning that the PCM product S21 was simulated using a default PCM wall layer model in the study. IDA ICE uses the enthalpy method which considers the hysteresis effect to simulate PCM (Mazzeo et al., 2020). The model calculates the heat capacity as a function of temperature and PCM state. The simulated PCM layer's performance followed the partial enthalpy curves during melting and solidifying.

ECONOMICAL CALCULATION

Discounted payback period

In the study, the payback period was calculated to evaluate the economic feasibility of novel technologies. As real estate companies prefer a payback time of around 10 years (Kuivjõgi et al., 2021), renovation scenarios were considered economically viable in the study only if they had a discounted payback period of less than 10 years. The discounted payback period can be calculated by equation (1) (Sirén, 2016):

$$N_d = \frac{\ln\left(1 - \frac{I_0}{A} r\right)}{\ln\left(\frac{1}{1+r}\right)} \quad (1)$$

in which N_d is the discounted payback period [a], I_0 is the investment cost [€], A is the annual net saving [€], r is the real interest rate.

Investment cost

The investment cost I_0 in equation (1) of each renovation technology was defined based on the feedback from the manufacturers and the installation professionals/workshops (Pappa et al., 2022). It is the sum of costs from manufacturing, auxiliary equipment and installation. Table 8 shows the investment costs of different renovation scenarios in each demo house.

	PASSIVE PACKAGE			VENTILATION PACKAGE			GENERATION PACKAGE		FINAL COMBINATION	
	INS	INS + WIN	INS + WIN + PCM	MEM 50%	MEM 100%	MEM 100% + RAHU	PV/T	SAHP	PAS + VEN + PV/T	PAS + VEN + SAHP
English demo house	475.62	517.81	590.29	33.40	33.40	64.89	57.59	81.75	712.76	736.93
Spanish demo house	424.61	465.94	516.00	33.20	33.20	45.41	31.91	31.71	593.32	593.12

Table 8 The investment cost [€/floor-m²] of different renovation scenarios for the English and Spanish demo house.

***Ins**: Bio-aerogel thermal insulation; **Win**: PV vacuum window; **PCM**: Phase change material; **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.

Annual net saving

The annual net saving *A* in equation (1) refers to the difference between the annual saving and expense. More specifically, it can be calculated by equation (2) in the study.

$$A = T_{elec} + T_{gas} - K_{maint} \qquad (2)$$

where T_{elec} and T_{gas} represent the annual net electricity and gas cost savings after renovation, K_{maint} is the annual maintenance expense for the renovation technologies.

For the cases containing PV vacuum windows or/and PV/T system, the annual saving also includes the annual income from sold electricity in addition to the annual net energy cost saving. The annual saving was calculated based on the English and Spanish energy prices for the first semester of 2022 in the study (see Table 9) (Eurostat, 2022). The annual maintenance expense for the PV/T system is 140 € and 210 € in the English and Spanish demo houses, respectively. The annual maintenance cost for SAHP is 180 € in both demo houses.

COUNTRY	NATURAL GAS	ELECTRICITY	ELECTRICITY SOLD TO GRID
UK	0.0823	0.232	0.18
Spain	0.0897	0.307	0.07

Table 9 Energy price [€/kWh] in the UK and Spain.

Real interest rate

The real interest rate *r* takes the impact of interest rate and inflation into account, which can be calculated by equation (3).

$$r = \frac{i - f}{1 + f} \qquad (3)$$

where *i* is the nominal interest rate and *f* is the inflation rate.

COUNTRY	INFLATION RATE *f*	NOMINAL INTEREST RATE *i*
UK	7.69%	0.88%
Spain	8.48%	1.56%

Table 10 The inflation rate and nominal interest rate in the UK and Spain.

In the study, the average inflation rate and nominal interest rate for the first semester of 2022 in the UK and Spain (see Table 10) were utilized to calculate the corresponding real interest rate (Rateinflation, 2023).

RESULTS

REFERENCE CASES BEFORE RENOVATION

Table 11 shows the breakdown of purchased energy, and the corresponding total primary energy and CO_2 emissions in the English and Spanish demo houses before renovation. The simulated total energy consumption was within 5% of the measured values after HDD correction (Hirvonen et al., 2022). The total purchased energy of the Spanish demo house was much lower than that of the English demo house. Space heating demand was the dominant energy-consuming factor in both demo houses. The Spanish demo house had a much better thermal insulation level of external walls and better airtightness than the English demo house. The heating degree hours in Valladolid are lower than that in Nottingham. Therefore, in the Spanish terraced house, the proportion of space heating consumption (74%) was lower than that (92%) in the English demon house.

In addition to energy consumption and CO_2 emissions, the indoor climate was also simulated (see Table 12). The indoor air temperature in the English demo house was always above the heating setpoint of 19.5°C since the

DEMO HOUSE	ENGLISH SEMI-DETACHED HOUSE	SPANISH TERRACED HOUSE
Gas heating, total	182.3	115
Space heating	182.3	99.2
DHW	–	15.7
Electricity, total	24.5	19.4
Equip+Light	8.6	19.2
HVAC aux	0.2	0.2
Space heating	7.4	–
DHW	8.3	–
Total purchased energy	206.8	134.4
Total primary energy	242.7	152.3
Total CO_2 emissions	42.7	26.6

Table 11 Simulated energy consumption (kWh/m²a) and CO_2 emissions (kg-CO_2/m²a) of the demo houses before renovation.

DEMO HOUSE	ENGLISH SEMI-DETACHED HOUSE	SPANISH TERRACED HOUSE
Thermal comfort		
Proportion of time indoor temperature is lower than 19.5°C [%]	0.0	–
Proportion of time indoor temperature is lower than 18°C [%]	–	5.1
Proportion of time indoor temperature is higher than 25°C [%]	0.4	11.9
Maximum air temperature [°C]	29.1	30.5
Indoor air quality		
Proportion of time indoor CO_2 concentration is lower than 1200 ppm [%]	100.0	41.3
Proportion of time indoor CO_2 concentration is lower than 1800 ppm [%]	100.0	98.1

Table 12 Simulated indoor climate of the demo houses before renovation.

demo house was continuously heated. As the heating setpoint for nighttime was 17°C, around 5% of the time indoor air temperature was lower than the daytime setpoint 18°C in the Spanish demo house. The share of time indoor temperature above 25°C in the Spanish demo house is much higher than that in the English demo house due to a higher outdoor temperature in Valladolid during summertime. The indoor CO_2 concentration level was used as the index to evaluate indoor air quality in the study. For the English demo house, the indoor CO_2 concentrations in bedrooms were maintained below 1200 ppm all year round due to the high air infiltration. About 57% of the time indoor CO_2 concentrations were between 1200 and 1800 ppm in the Spanish demo house.

RENOVATION PACKAGE SIMULATION

English semi-detached house

Table 13 presents the purchased energy, primary energy as well as CO_2 emissions of the English demo house after renovation with different renovation packages. The conduction and infiltration heat loss through the building envelopes dominated the space heating load. Bio-aerogel thermal insulation had a significant positive impact on the thermal insulation performance of external walls and roof. It led to the largest effect among technologies in the passive package, reducing primary energy and CO_2 emissions by almost 40%.

Only the south façade windows were replaced by PV vacuum windows. The PCM layers acted more like a passive cooling method which absorbed excess heat during summer daytime and increased building thermal mass, slightly reducing space heating energy demand. Therefore, PV vacuum windows and PCM only reduced primary energy further by 4% and 1%, respectively, with corresponding CO_2 emissions reductions of 3% and 1%.

As for the ventilation package, in addition to the impact on the thermal insulation of external walls and roof, renovating building envelopes with insulating breath membrane also significantly improved the building airtightness, decreasing heat loss through air infiltration. Thus, insulating breath membrane brought an even higher primary energy and CO_2 emissions reduction than bio-aerogel thermal insulation in the 50% airtightness improvement case. Then, further improving building airtightness to 100% led to 7% and 8% more reduction in primary energy and CO_2 emissions due to further reduced heat loss through air infiltration. Therefore, the main energy efficiency impact came from the improved thermal insulation instead of improved airtightness.

Installing RAHUs resulted in increased heating demand to heat the boosted supply air rate in winter. If the living room and bedrooms were equipped with RAHUs in the 100% airtightness improvement cases, the primary energy and CO_2 emissions reduction dropped slightly.

Regarding the generation technologies, PVT system led to a much lower reduction in both primary energy and CO_2 emissions. The backup heater consumed more energy to cover space and DHW heating demand in PVT system due to the limited solar radiation in Nottingham. In comparison, SAHP could cover more proportion of the space and DHW heating demand in the English demo house. The backup heater for SAHP consumed less energy compared to PVT system. Thus, the primary energy and CO_2 emissions reduction were significantly higher after installing SAHP. Correspondingly, the final combination including SAHP has a larger potential in decreasing primary energy and CO_2 emissions than that including PVT system.

Table 13 also shows the indoor climate change of the English semi-detached house after renovation. Almost all the time indoor temperature after renovation was maintained in the comfortable range from 19.5 to 25°C. The insulating breath membrane brought a higher indoor CO_2 concentration level due to the airtightness improvement, especially for the 100% airtightness improvement case. Then, the indoor CO_2 concentration decreased back to always below 1200 ppm after installing RAHU for a boosted ventilation rate.

	PASSIVE PACKAGE			VENTILATION PACKAGE			GENERATION PACKAGE		FINAL COMBINATION	
	INS	**INS + WIN**	**INS + WIN + PCM**	**MEM 50%**	**MEM 100%**	**MEM 100% + RAHU**	**PV/T**	**SAHP**	**PAS + VEN + PV/T**	**PAS + VEN + SAHP**
Gas total	102.7	107.9	107.1	96.5	80.6	87.8	171.9	77.1	57.8	10.2
SH + DHW	102.7	107.9	107.1	96.5	80.6	87.8	–	–	–	–
Backup heating	–	–	–	–	–	–	171.9	77.1	57.8	10.2
Electricity total	22.4	11.9	11.8	21.9	21.2	21.5	19.1	58.4	9.7	32.6
Equip + Light	8.6	6.4	6.4	8.6	8.6	8.6	6.4	8.6	5.7	7
HVAC aux	0.1	0.1	0.1	0.1	0.1	0.4	5.6	0.4	1	0.4
Space heating	5.4	5.4	5.3	4.9	4.2	4.2	7.1	7.4	3	3.1
DHW heating	8.3	0	0	8.3	8.3	8.3	0	0	0	0
Heat pump	0	0	0	0	0	0	0	42	0	22.1
Solar PV total		2.7	2.7				13.8		13.7	
Used		2.3	2.3				9.2		7.1	
Sold		0.4	0.4				4.6		6.6	
Total purchased	125.1	119.8	118.9	118.4	101.8	109.3	191	135.5	67.5	42.8
Reduction [%]	40%	42%	43%	43%	51%	47%	8%	34%	67%	79%
Primary energy	149.7	139.8	138.7	141.9	122.9	131.5	222.9	174.7	79.9	60.4
Reduction [%]	38%	42%	43%	42%	49%	46%	8%	28%	67%	75%
CO_2 emissions	26.0	24.7	24.5	24.6	21.3	22.8	39.3	29.1	14.0	9.6
Reduction [%]	39%	42%	43%	42%	50%	47%	8%	32%	67%	77%
Indoor climate										
T < 19.5°C [%]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
T > 25°C [%]	0.5	0.1	0.1	0.7	0.9	0.8	0.4	0.4	0.2	0.2
T_max [°C]	29.0	26.8	26.4	29.3	29.4	29.4	29.1	29.1	27.2	27.2
CO_2 < 1200 [%]	100.0	100.0	100.0	96.8	3.3	100.0	100.0	100.0	100.0	100.0
CO_2 < 1800 [%]	100.0	100.0	100.0	100.0	6.8	100.0	100.0	100.0	100.0	100.0

Table 13 Simulated energy consumption (kWh/m^{2}a), CO_2 emissions (kg-CO_2/m^{2}a) and indoor climate of the English semi-detached house after renovation.

***SH**: Space heating; **DHW**: Domestic hot water; **T < 19.5°C/T > 25°C**: Proportion of time indoor temperature is lower than 19.5°C or higher than 25°C; **T_max**: Maximum air temperature; **CO_2 < 1200/1800**: Proportion of time indoor CO_2 concentration is lower than 1200 or 1800 ppm.

Spanish terraced house

As shown in Table 14, the energy consumption and CO_2 emissions of the Spanish terraced house were reduced at different levels after renovating with renovation packages and their combinations. Compared to the English demo house, thermal conduction through building envelopes accounted for a higher proportion of the total heating load in the Spanish demo house. Thus, the energy saving and CO_2 emissions reduction in percentage brought by bio-aerogel thermal insulation in the Spanish demo house is slightly higher than that in the English demo house.

Then, mainly due to a higher solar radiation level, the impact of PV vacuum windows in the Spanish demo house was slightly larger than that in the English demo house, reducing primary energy and CO_2 emissions by 6%. Installing PCM layer also had a minor positive impact since it increased building thermal mass.

In terms of insulating breath membrane's effect, as the building airtightness change of the Spanish demo house was not as significant as that in the English demo house, the primary energy and CO_2 emissions reduction were slightly lower for both airtightness improvement cases. After installing RAHUs, the reduction in primary energy and CO_2 emissions was lowered due to the increased space heating demand caused by a higher ventilation rate.

	PASSIVE PACKAGE			VENTILATION PACKAGE			GENERATION PACKAGE		FINAL COMBINATION	
	INS	INS + WIN	INS + WIN + PCM	MEM 50%	MEM 100%	MEM 100% + RAHU	PV/T	SAHP	PAS + VEN + PV/T	PAS + VEN + SAHP
Gas total	58.0	51.1	50.2	68.1	67.2	77.5	97.1	45.6	33.1	5.9
SH + DHW	58.0	51.1	50.2	68.1	67.2	77.5	97.1	45.6	33.1	5.9
Electricity total	19.3	18.2	18.2	19.3	19.3	19.8	12.5	39.8	12.7	33.3
Equip + Light	19.2	18.1	18.1	19.2	19.2	19.2	12.4	19.2	12.4	18.4
HVAC aux	0.1	0.1	0.1	0.1	0.1	0.6	0.1	0.2	0.3	0.5
Heat pump	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.4	0.0	14.4
Solar PV total		1.1	1.1				12.8		12.8	1.1
Used		1.1	1.1				6.9		7.0	1.1
Sold		0.0	0.0				5.9		5.8	0.0
Total purchased	77.2	69.3	68.4	87.4	86.5	97.3	109.6	85.4	45.8	39.2
Reduction [%]	43%	48%	49%	35%	36%	28%	18%	36%	66%	71%
Primary energy	91.1	82.1	81.2	102.0	101.0	112.8	122.7	108.9	54.6	56.6
Reduction [%]	40%	46%	47%	33%	34%	26%	19%	29%	64%	63%
CO_2 emissions	15.2	13.6	13.4	17.2	17.0	19.2	20.6	16.6	9.0	7.5
Reduction [%]	43%	49%	49%	35%	36%	28%	23%	37%	66%	72%
Indoor climate										
T < 18°C [%]	0.0	0.0	0.0	4.6	0.0	0.2	5.1	5.1	0.0	0.0
T > 25°C [%]	11.4	10.1	10.5	12.4	12.0	9.9	11.7	11.8	8.3	8.3
T_max [°C]	29.6	29.1	28.5	29.9	30.2	30.2	30.4	30.4	28.3	28.3
CO_2 < 1200 [%]	43.9	44.6	45.4	35.8	24.2	99.5	41.2	41.2	99.5	99.5
CO_2 < 1800 [%]	98.6	98.8	98.9	97.9	95.7	100.0	98.1	98.1	100.0	100.0

Table 14 Simulated energy consumption (kWh/m²a), CO_2 emissions (kg-CO_2/m²a) and indoor climate of the Spanish terraced house after renovation.

For generation technologies, compared with its impact in the English demo house, the primary energy and CO_2 emissions reduction achieved with PVT system increased moderately in the Spanish demo house due to more abundant solar radiation in Valladolid. However, SAHP is still a better energy-saving and emission-conserving technology than the PVT system in the Spanish demo house.

Nevertheless, the final combination including SAHP had a similar effect to that including PVT system, reducing primary energy and CO_2 emissions by over 60%. The technologies in the passive and ventilation package reduced the space heat demand significantly. Thus, if the Spanish demo house was renovated with the final combinations, either PVT system or SAHP would not require as much backup heating as that when only the generation technologies were applied in the renovation.

The renovation technologies resulted in variable indoor climate change seen in Table 14. Compared with the case before renovation (see Table 12), the indoor temperature level was improved remarkably after renovating with bio-aerogel thermal insulation and insulating breath membrane. As for the indoor air quality, insulating breath membrane had a negative impact on indoor CO_2 concentration, while installing RAHU lowered the indoor CO_2 concentration to below 1200 ppm all year round.

ENERGY COST SAVINGS & DISCOUNTED PAYBACK PERIODS

With the energy consumption reduction brought by renovation, the annual energy costs of both demo houses were reduced at different levels after renovating with most renovation scenarios (see Table 15). Nevertheless, for the Spanish demo house, installing SAHP slightly increased the energy cost due to raised electricity consumption and high electricity price.

Table 16 shows the discounted payback periods of different renovation scenarios for the English demo house. Although bio-aerogel thermal insulation conserved a significant energy-saving potential, its discounted payback period was still far exceeding the expected 10-year payback period due to the high investment cost. Then, as PV vacuum windows and PCM required much lower investment cost than bio-aerogel thermal insulation, the payback periods of the rest renovation cases in the passive package were lower than the case where only bio-aerogel thermal insulation was included.

As the investment cost of insulating breath membrane was even lower than 1/10 of that of bio-aerogel thermal insulation, insulating breath membrane's discounted payback period was maintained between 3–4 years. For the final renovation case in the ventilation package, the installation of RAHU required more investment cost and had higher energy consumption than the cases where only insulating breath membrane was applied. Its discounted payback period increased to a certain extent.

Compared with insulating breath membrane, PV/T system required more investment cost while leading to a lower energy consumption reduction. Therefore, PV/T system had a much longer payback period, over 10 years' payback period. Although installing SAHP reduced energy consumption significantly, the annual net income was always negative value because it consumed more electricity than before renovation and the electricity price was almost three times the natural gas price. There was no payback period for SAHP. Finally, both final combinations possessed a discounted payback period are over 20 years.

The discounted payback periods of all renovation scenarios for the Spanish demo house are also shown in Table 16. For the Spanish demo house, all the renovation scenarios in the passive and ventilation packages had a longer payback period than in the English demo house.

As PVT system had a much higher energy reduction potential under Spanish climate conditions than under English climate conditions, its discounted payback period was much shorter than that in the English demo house. Similarly, SAHP also had no payback period in the Spanish demo house.

In addition, the investment costs of renovation scenarios including bio-aerogel thermal insulation were calculated based on the 10-year payback period assumption (see Table 17). Comparing Tables 8 and 17, the investment cost of bio-aerogel thermal insulation should be reduced by 78% and 82% in the English and Spanish demo houses to reach a 10-year payback period. The investment cost of other two renovation scenarios in the passive package shall be reduced by 74% and 77% for the English demo house, and 81% and 82% for the Spanish demo houses.

As SAHP had no payback period, the final combination including SAHP required a higher investment cost reduction in percentage, 79% and 88% in the English and

	PASSIVE PACKAGE			VENTILATION PACKAGE			GENERATION PACKAGE		FINAL COMBINATION	
	INS	INS + WIN	INS + WIN + PCM	MEM 50%	MEM 100%	MEM 100% + RAHU	PV/T	SAHP	PAS + VEN + PV/T	PAS + VEN + SAHP
English demo house	814.3	1046.7	1057.0	886.8	1057.0	980.4	244.0	91.8	1582.8	1421.3
Spanish demo house	1534.3	1819.7	1843.8	1264.1	1288.2	966.8	1111.1	–11.8	2805.2	1645.9

Table 15 The annual net energy cost savings [€] of energy renovations in the English and Spanish demo houses.

	PASSIVE PACKAGE			VENTILATION PACKAGE			GENERATION PACKAGE		FINAL COMBINATION	
	INS	INS + WIN	INS + WIN + PCM	MEM 50%	MEM 100%	MEM 100% + RAHU	PV/T	SAHP	PAS + VEN + PV/T	PAS + VEN + SAHP
English demo house	25.4	23.3	24.8	3.7	3.2	6.0	17.4	–	22.3	25.6
Spanish demo house	27.8	26.9	28.0	6.1	6.1	9.7	7.1	–	24.9	32.8

Table 16 The discounted payback periods of energy renovations in the English and Spanish demo houses.

	PASSIVE PACKAGE			FINAL COMBINATION	
	INS	INS + WIN	INS + WIN + PCM	PAS + VEN + PV/T	PAS + VEN + SAHP
English demo house	102.62	132.95	134.25	199.14	156.44
Spanish demo house	75.24	89.24	90.42	133.21	71.89

Table 17 The required investment cost [€/floor-m^2] of renovation scenarios including bio-aerogel thermal insulation to acquire a 10-year payback period.

Spanish demo houses, than that including PV/T system, 72% and 78% in the English and Spanish demo houses.

DISCUSSION

Renovating the existing buildings offers an important opportunity to reduce global energy consumption and GHG emissions. Building energy renovations can be implemented through diverse approaches, for example, reducing building energy demand, utilizing heat recovery for heat flexibility and increasing renewable energy sources. The paper studies several novel renovation technologies relevant to these three approaches.

The study based on building-level simulations reveals the CO_2 emissions reduction potential of old residential houses in English and Spanish climate conditions. The feasibility of novel renovation technologies was studied by simulating their impact in both climate conditions and calculating the discounted payback periods. Thus, the study can act as a guideline for choosing effective novel renovation technologies for both climate conditions. In addition, the presented performance and challenges of these analyzed technologies are instructive for their development into competitive products in the market.

According to the building-level simulation results, bio-aerogel thermal insulation and insulating breath membrane are the most suggested technologies in the passive and ventilation packages to reduce building CO_2 emissions for both climate conditions. As for the generation package, SAHP is a more recommended generation technology for lower CO_2 emissions than PVT system in both climate conditions.

Commonly, space heating demand shares a larger proportion of building energy demand in colder regions than in warm regions. Improving building envelopes' thermal insulation is beneficial for space heating demand reduction. Thus, the impact of thermal insulating measures on building energy consumption and CO_2 emissions should be more significant in much colder climate conditions. In addition, thermal insulation performance is also affected by building characteristics, such as building airtightness and existing thermal transmittance of building envelopes.

Both solar-related generation technologies' performance depends on local global solar radiations. Compared with PV/T system, global solar radiation differences have less influence on the performance of SAHP. The solar collector in SAHP functions more like an ambient heat exchanger than a solar thermal collector because it still transfers heat from ambient air through convection when solar radiation is unavailable.

In comparison with other renovation technologies, the current investment cost of bio-aerogel thermal insulation is extremely high, which affects the economic feasibility of all the renovation scenarios including the technology. The capital cost of sustainable energy technologies, such as solar-PV, has experienced a significant decrease following the development and innovation in related fields during the past several decades (Elia et al., 2021). Similarly, considering that the technology is still in the early stages of development, its cost is expected to decrease significantly as it is further marketed. Thus, bio-aerogel thermal insulation may have the potential to become a cost-effective mainstream insulation product in the future.

In the study, SAHP is economically unfeasible due to the high electricity prices. The electricity price is maintained at a high level due to the energy shortage caused by the war between Ukraine and Russia, the European carbon neutrality strategy, etc. If electricity prices lower with the end of the war and the continued advancement of the carbon neutral strategy, it will make SAHP economically feasible.

Nevertheless, there are some limitations existing in the economical calculations. The discounted payback periods were calculated according to the inflation rate, nominal interest and energy price in the first semester of 2022. These factors can change variably over time, leading to different discounted payback periods to the results shown in the study. If the real interest rate increases following the decreased inflation rate and nominal interest rate after the war, it results in even longer payback periods for these novel renovation scenarios. Considering the current energy situation, it is also possible that energy prices will not decrease or even increase. If the electricity and natural gas prices increase after renovation, the financial viability of energy renovation improves considerably since the increasing energy prices shorten payback periods. For instance, in the English demo house, the payback period of bio-aerogel thermal insulation could be shortened from 25.4 years to 20.6 years when the electricity and natural gas prices increase by 50%.

Besides, limitations also exist in the building-level simulations. For instance, the generation technologies were simulated according to the design information or laboratory test results. The technologies' settings in the simulations may be different from those in actual renovations due to commissioning issues. It will lead to an energy saving and CO_2 emissions reduction gap between the simulations and actual conditions. In terms of the building models' setting, a single usage behavior has been used in the simulations even if the actual usage of the residential houses typically varies significantly depending on the occupants. Besides, although the weather conditions may be variable between the years, a single weather year was used in the simulations.

Furthermore, future research based on the study will investigate the endurance and long-term performance of these novel renovation technologies in more climate conditions. This will help researchers understand renovation technologies' effectiveness and potential limitations better. More field studies or actual demonstrations of the novel renovation technologies in existing buildings will also be beneficial to test their performance and evaluate their effect on energy consumption and CO_2 emissions reduction.

CONCLUSIONS

The paper studies several novel renovation technologies and their combinations' CO_2 emissions reduction potential in English and Spanish climate conditions by building-level simulations. In addition, the study also assesses energy renovations' economic feasibility by calculating their discounted payback periods.

The simulations show a significant CO_2 emissions reduction can be achieved with novel renovation technologies and their combinations. The final combination scenario including SAHP reduces CO_2 emissions maximumly by 77% and 72% in the English and Spanish demo houses, respectively. Besides, some of the renovation technologies, such as RAHU, have a positive impact on indoor climates.

The technologies improving the envelopes' thermal insulation level, such as bio-aerogel thermal insulation and insulating breath membrane, conserve the most significant CO_2 emissions reduction in climate conditions where space heating demand dominates the building energy usage. PV vacuum windows can bring a certain level of CO_2 emissions reduction due to their low thermal transmittance and electricity generation capacity. They are more suitable for climate conditions with high solar radiation for improved electricity generation. The PCM layer under the ceilings is not recommended due to the minor impact on CO_2 emissions.

For leaky buildings in cold climates, insulating breath membrane is even more recommended for CO_2 emissions reduction than bio-aerogel thermal insulation. In addition to its thermal insulating characteristic, insulating breath membrane also improves the building airtightness for lower heat loss from air infiltration. Nevertheless, it has a negative impact on indoor air quality. Installing RAHU can solve the negative indoor air quality impact at the cost of a slight decrease in CO_2 emissions savings.

As for the generation package, SAHP saves more CO_2 emissions than PV/T system in cold climate conditions. Compared with SAHP, the performance of PVT system more depends on the local solar radiation. Thus, the final combination scenario including SAHP is a better option to acquire the maximum CO_2 emissions reduction, which saves CO_2 emissions over 70% in both demo houses.

Regarding the economic feasibility, insulating breath membrane is the most cost-effective renovation technology among them, with a discounted payback period much shorter than 10 years. Nevertheless, some of the renovation technologies have much longer payback periods or even have no payback period. Bio-aerogel thermal insulation has high manufacturing cost resulting in discounted payback periods longer than 20 years. RAHU has no payback period because it focuses on improving indoor climates instead of saving energy usage. SAHP is not economically feasible since this technology cannot reduce annual energy costs due to the higher electricity prices in the UK and Spain.

Although some of the analyzed technologies are economically unfeasible in actual renovations currently, these technologies still have the potential to be applied in the renovations due to their effect on improved indoor climate and significant CO_2 emissions reduction. They can become feasible renovation methods considering the manufacturing cost reduction following their industrialization and commercialization.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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