CO_2 emissions reduction potential of sustainable residential renovations in England

Yangmin Wang[1*], Ke Qu[2], Juha Jokisalo[1,3], and Risto Kosonen[1,3,4]

[1] Department of Mechanical Engineering, Aalto University, Finland
[2] Department of Architecture and Built Environment, University of Nottingham, UK
[3] FinEst Centre for Smart Cities, TalTech, Estonia
[4] College of Urban Construction, Nanjing Tech University, China

[*]*Corresponding email: yangmin.wang@aalto.fi*

ABSTRACT

Renovating the residential stock plays an important role in achieving carbon neutrality in Europe. The study evaluates several novel renovation technologies' effects on CO_2 emissions and indoor climate by building level simulations. An English semi-detached house was selected as the demo house. The analysed renovation 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. They were classified into the passive, ventilation and generation packages, and simulated by packages and final combinations. Thermal insulating technologies, bio-aerogel thermal insulation and insulating breath membrane, have the largest CO_2 emissions reduction potential, resulting in over 40% reduction by single technology. The demo house's CO_2 emissions can be reduced by over 60% after renovating with either final combination of the novel renovation technologies.

KEYWORDS: Building energy efficiency, CO_2 emissions, Energy renovations, Indoor climate

1. INTRODUCTION

The building sector, the largest single contributor to energy consumption and carbon emissions, accounts for 40% of total energy consumption and 36% of greenhouse gas (GHG) emissions in the EU (CITY MINDED, 2021). Thus, it is significant to improve building energy efficiency for achieving carbon neutrality by 2050. The new buildings should be constructed according to the building energy performance regulations. However, new energy efficient constructions only share a minority of the EU building stock, while the existing buildings with poor energy efficiency dominate the building stock. Roughly 75% of the EU building stock is energy inefficient at present (*EU Buildings Factsheets*, 2016). Therefore, it is important to renovate the energy inefficient buildings for carbon neutrality target.

To accelerate renovation speed of the EU building stock, EU commission published its Renovation Wave Strategy (*Renovation Wave*, 2020). Against this background, SUREFIT project was initiated and funded by the commission, aiming at finding sustainable solutions for affordable retrofit of the EU residential buildings. The goal of this project is to attain almost zero energy consumption by reducing heat loss via building envelopes and energy consumption for heating, cooling, ventilation, and lighting while increasing the proportion of renewable energy in the structure. Several representative residentials from different EU countries were selected to serve as the demo buildings to implement novel energy technologies.

The paper focuses on analysing the impact of novel renovation technologies and their combinations on energy consumption, CO_2 emissions, and also indoor climates in an English demo house through simulation. It also reveals the maximum energy saving and CO_2 emissions reduction potential of the demo house with the final combinations of renovation technologies.

2. METHOD

2.1 Simulation setup

IDA ICE, a dynamic simulation tool, was utilized to simulate the demo house before and after renovation in the study. To derive hourly energy demand and indoor climate profiles, the house model was constructed using input data from design information or the online database TABULA Webtool (*TABULA WebTool*, 2021). The demo house model acted as the reference cases for renovation technologies simulations.

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

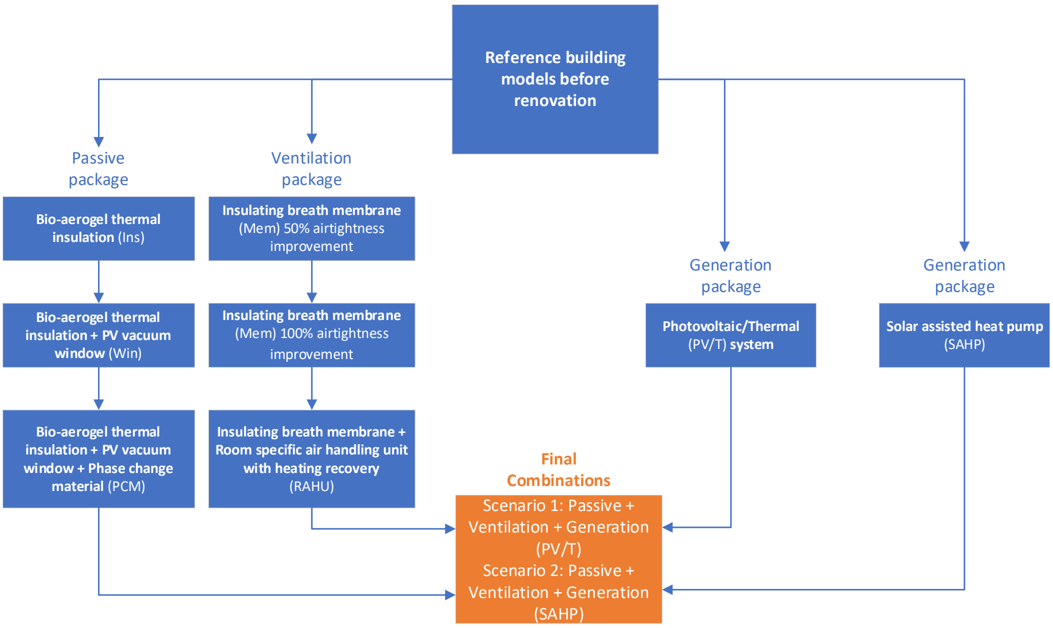

Figure 1. Simulation of renovation packages in IDA ICE.

2.2 Demo building description

The English demo house is a semi-detached house in Nottingham. The demo house comprises an attic on the top floor, three bedrooms and a bathroom on the first floor, and a living room and a kitchen on the ground floor. It was constructed with solid brick external walls without thermal insulation, non-insulated pitched roof and 100 mm insulated loft. The ground floor is concrete without thermal insulation. The U-values of external wall, roof and external floor are 2.10, 0.22 and 0.85 W/m^{2}K, respectively. All the windows were fully renovated with double glazing in 2012, the U-values of which are 2.4 or 2.5 W/m^{2}K after last renovation. In terms of other window properties, the solar heat gain coefficient, solar transmittance and visible transmittance are 0.76, 0.70 and 0.81. According to the field test, the air leakage rate, n_{50} of the demo house is 16.1 ACH.

As for HVAC systems, the kitchen and attic in the demo house are heated by electric radiators, while space heating for other living spaces are supplied by a natural gas boiler (24 kW) and water radiators.

Energy demand for domestic hot water (DHW) heating is covered by an electric water heater. The DHW usage is around 20 L/day/person. There is no cooling system in the house. Most living spaces are naturally ventilated through infiltration and openable windows except exhaust ventilation for kitchen, bathroom and toilet. The exhaust air flow rate for kitchen, bathroom and toilet is 15, 10 and 3 L/s.

Since space heating accounts for the majority of the residential energy usage in cold climates, defining appropriate heating setpoint and schedules is important for reflecting energy consumption conditions in the existing demo house accurately. Table 1 shows the heating setpoint and schedules applied in the English demo house.

Table 1. Heating setpoint and schedules of the English semi-detached house.

Living space	Heating setpoint & schedules
Most of the living spaces except kitchen and attic	**All year round**, 19.5 °C, all day
Kitchen/Dining room	**Weekdays**: 19.5 °C [7:00-8:00, 17:00-18:00], **Weekends & Holidays**: 19.5 °C [9:00-10:00, 12:00-13:00, 17:00-18:00]
Attic	**From 1 Apr to 30 Sep, Weekends**: 19.5 °C [18:00-23:00]

2.3 Primary energy and carbon emissions

The primary energy factors (PEFs) were introduced to convert the purchased energy consumption into the primary energy demand in the study. The PEFs of natural gas and electricity are 1.13 and 1.15 kWh/kWh in the UK. The CO_2 emissions factors can be utilized to calculate the building CO_2 emissions according to the simulated purchased energy, which are 203 and 231 kg-CO_2/MWh for natural gas and electricity, respectively.

2.4 Renovation packages

2.4.1 Passive package

The passive package consists of bio-aerogel thermal insulation, PV vacuum glazing window and phase change material (PCM). Table 2 shows detailed properties of the renovation technologies. Bio-aerogel thermal insulation made of starch-based aerogel is a sustainable insulating material for building envelopes. It has good thermal insulation and favorable mechanical properties (Nita *et al.*, 2020). For the demo house, it was made into prefabricated panels installed on the outsides of external walls and roofs.

Table 2. Properties of renovation technologies in the passive package.

Renovation technology	Properties
Bio-aerogel thermal insulation	Thermal conductivity [W/mK]: 0.024, 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]: 12.8
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

PV vacuum window is a daylight-management device with PV components integrated in the form of thin-elastic-films (Jarimi *et al.*, 2020). It comprises self-cleaning coated glass, vacuum filled layer and thin film PV glass with additional glass cover. In addition to its electricity production capacity, PV vacuum window has good performance in terms of thermal insulation, acoustic and sound reduction. PCM can release or absorb thermal energy through solid-liquid phase change to provide useful heating or cooling. In the study, PCM product S21, a salt hydrate, was selected as independent layers installed under the ceilings of the demo house. It starts to melt at 18°C, reach partial enthalpy peak at 27 °C, and ends at 36 °C (Wang *et al.*, 2022).

2.4.2 Ventilation package

The ventilation package includes insulating breath membrane and room specific air handling unit with heat recovery (RAHU). Insulating breath membrane can be viewed as another thermal insulating measures for building envelopes which also improves the building airtightness (WINCO technologies, 2021). The demo house's external walls and roof were covered by insulating breath membrane from the outside. As the air leakage rate of the demo house is unknown after renovating with insulating breath membrane, two cases with different assumed air leakage rates were simulated in this study: 50% airtightness improvement (the average value of the existing building's infiltration rate 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 system positioned above window frameworks (Barreto *et al.*, 2022). It consists of fans, promoting air circulation, and heat pipes, utilizing exhaust heat to heating supply air. RAHUs were installed in the living room and bedrooms. Table 3 shows more properties of the renovation technologies in the ventilation package.

Table 3. Properties of renovation technologies in the ventilation package.

Renovation technology	**Properties**
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]: 8.1, Airtightness (100% improvement) at 50 Pa [ACH]: 0.14
RAHU	Air flow rate [L/sm^2]: 0.6, Pressure rise by supply and return fan [Pa]: 15, Heat recovery efficiency: 0.76

2.4.3 Generation package

The generation package contains photovoltaic/thermal (PV/T) system and solar assisted heat pump (SAHP). PV/T system is a hybrid technology combining photovoltaics and thermal energy production (Das, Kalita and Roy, 2018). The system consists of PV/T panels, a hot water tank and a backup heater. The PV/T panels combine photovoltaic solar cells, turning sunlight into electricity, and a solar thermal collector, transferring the PV module's waste heat to a heat transfer fluid. The system has a higher overall efficiency than solar photovoltaic or solar thermal alone. The analysed SAHP in the study is a heat pump, which is equipped with an evaporator connected to solar collectors indirectly (Fan *et al.*, 2021). However, there is a mismatch between solar radiation availability and heating energy demand. Thus, the solar collectors operate more like ambient heat exchangers as they also extract heat from ambient air through convection when solar radiation is unavailable. SAHP has a much higher COP than conventional heating system, such as boilers. Specific properties of generation measures are presented in Table 4.

Table 4. Properties of renovation technologies in the generation package.

Renovation technology	**Properties**
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]: 14, Volume of hot water tank [m^3]: 0.8
SAHP	Total heating capacity [kW]: 11, COP: 4, Dimensions of each solar collector panel [m]: 2.1×0.81, Panel number: 4, Conversion factor η_0: 0.7, Loss coefficient a_1 [W/m^{2}K]: 4, Loss coefficient a_2 [W/m^{2}K]: 0.005

3. RESULTS

Table 5 shows the purchased energy, primary energy, CO_2 emissions and indoor climate of the English semi-detached house before and after renovations. Space heating demand accounted for over 90% of building energy usage before renovation. The majority of space heating demand was caused by conduction and infiltration heat loss through the building envelope. The thermal insulation performance of external walls and roof was significantly improved by the use of bio aerogel thermal insulation. It had the largest impact among all the passive package solutions, cutting down both primary energy use and CO_2 emissions by approximately 40%.

Table 5. Simulated energy consumption (kWh/m^2a), CO_2 emissions ($kg\text{-}CO_2/m^2a$) and indoor climate of the English semi-detached house before and after renovation.

		Passive package			**Ventilation package**			**Generation package**		**Final combination**	
	Ref	**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	182.3	102.7	107.9	107.1	96.5	80.6	87.8	171.9	77.1	57.8	10.2
SH + DHW	182.3	102.7	107.9	107.1	96.5	80.6	-	-	-	-	-
Backup heating	-	-	-	-	-	-	87.8	171.9	77.1	57.8	10.2
Electricity total	24.5	22.4	11.9	11.8	21.9	21.2	21.5	19.1	58.4	9.7	32.6
Equip + Light	8.6	8.6	6.4	6.4	8.6	8.6	8.6	6.4	8.6	5.7	7.0
HVAC aux	0.2	0.1	0.1	0.1	0.1	0.1	0.4	5.6	0.4	1.0	0.4
Space heating	7.4	5.4	5.4	5.3	4.9	4.2	4.2	7.1	7.4	3.0	3.1
DHW heating	8.3	8.3	0.0	0.0	8.3	8.3	8.3	0.0	0.0	0.0	0.0
Heat pump	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	42.0	0.0	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	206.8	125.1	119.8	118.9	118.4	101.8	109.3	191.0	135.5	67.5	42.8
Reduction [%]	-	40%	42%	43%	43%	51%	47%	8%	34%	67%	79%
Primary energy	242.7	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	42.7	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	0.0
T > 25.0 °C [%]	0.4	0.5	0.1	0.1	0.7	0.9	0.8	0.4	0.4	0.2	0.2
T_max [°C]	29.1	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	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	100.0	6.8	100.0	100.0	100.0	100.0	100.0

***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.

Only the windows on the south facade, accounting for 36% of the total window area, were changed to PV vacuum windows. The PCM layers beneath the ceiling performed more like a passive cooling system, absorbing heat during warm days to lower the maximum indoor temperature and increase building thermal mass to marginally lower space heating demand. Consequently, installing PV vacuum windows and PCM only resulted in 4% and 1% decreases in primary energy, respectively, with equivalent decreases in CO_2 emissions of 3% and 1%.

Regarding the ventilation package's effects, renovating building envelope with insulating breath membrane considerably increased building airtightness, which reduced heat loss from air infiltration in addition to having a similar effect on the thermal insulation performance of external walls and roof. It resulted in a primary energy reduction of 42% or 49% depending on whether the building's airtightness was improved by 50% or 100%. Correspondingly, CO_2 emissions were decreased by 42% or 50%, respectively. The minor difference between two case shows that better thermal insulation had a more significant impact on building energy efficiency than improved airtightness.

For boosted ventilation rate, installing RAHU resulted in slightly more electricity consumption for fans and higher heating demand to heat supply air in winter. When airtightness was improved by 100% after renovating with insulating breath membrane, the primary energy and CO_2 emissions reductions fell to 46% and 47% if the living room and bedrooms were equipped with RAHUs.

Installing PVT system only led to 8% reduction in primary energy and CO_2 emissions. Due to Nottingham's low solar radiation, the backup heater consumed much energy to meet space and DHW heating demand. In contrast, SAHP's capacity essentially met the requirement for space and DHW heating in the English demo house. Compared to PVT system, the backup heater for SAHP used less energy. Thus, primary energy use and CO_2 emissions were cut by 28% and 32%, respectively, after installing SAHP.

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.

4. DISCUSSION

The major target of the study is to analyse the impact of several renovation technologies in an English semi-detached house. Thus, it can be treated as a reference to choose appropriate novel renovation technologies for similar types of residentials in similar climate conditions.

Nevertheless, there are also some limitations existing in the simulations. The renovation technologies were simulated based on available design information or laboratory test. It is predictable to show a performance gap between the simulations and actual conditions due to commissioning issues. Besides, although weather conditions vary between years, only a single weather year was utilized in the simulations.

In addition to simulated impact at the building level, choosing appropriate renovation technologies also depend on their economic feasibility. The economical analyzation of the novel renovation technologies will be carried out in the future.

5. CONCLUSIONS

The study presents several novel renovation technologies' impacts on energy consumption, CO_2 emissions and indoor climate in an English demo house by simulation. The simulation results show that the analysed novel renovation technologies and their combinations can reduce CO_2 emissions significantly. The English demo house's CO_2 emissions decreased by up to 77% when it was renovated with the final combination scenario including SAHP. Besides, some of the renovation technologies, such as RAHU, have a positive effect on indoor climates.

Bio-aerogel thermal insulation is the most effective measure, reducing CO_2 emissions by 40%, in the passive package. Thus, renovating the building envelopes for better thermal insulation performance is an effective way to reduce CO_2 emissions of old residentials in cold climates. In compassion, PV vacuum windows and PCM have less effect on CO_2 emissions, which only led to 3% and 1% reduction, respectively.

Insulating breath membrane, another thermal insulating measure in the ventilation package, has even larger CO_2 emissions reduction potential than bio-aerogel thermal insulation. It brought 42% or 50% CO_2 emissions reductions for the English demo house corresponding to 50% or 100% airtightness improvement assumption. Therefore, in addition to thermal insulation improvement, improving building airtightness to reduce heat loss through infiltration can significantly enhance the CO_2 emissions conservation potential of leaky residentials in cold climates.

Nevertheless, the accompanied building airtightness improvement led to an increased indoor CO_2 concentration level. Then, installing RAHUs lowered down indoor CO_2 concentrations always below 1200 ppm at the price of CO_2 emissions reduction decreasing to 47%. To guarantee a good indoor air quality after renovation, the two technologies in the ventilation package should be included in the renovation scenarios at the same time.

As for generation technologies' impact, the installation of SAHP resulted in CO_2 emissions reduction by 32%, much higher than the 8% brought by PV/T system. Compared with PV/T system, the performance of SAHP is less depending on the local solar radiation level. It can operate as an air source heat pump when solar radiation is unavailable. Thus, SAHP is a much more recommended renovation technologies for reducing CO_2 emissions than PV/T system in such climate conditions without sufficient solar radiation.

ACKNOWLEDGEMENT

The study is part of the SUREFIT and FINEST Twins projects. SUREFIT project is funded by European Union (Horizon 2020 programme, Grant number: 894511). FINEST Twins project is funded by European Union (Horizon 2020 programme, Grant No. 856602) and the Estonian government." The authors would like to thank the research partners of the SUREFIT project, AMSolutions, Faculdade Santa Maria, ISQ Group and the University of Nottingham, and also the industrial partners involved in R&D process of Surefit technologies, including PCM Products, WINCO technologies, Solimpeks.

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