Assessment and optimisation of life cycle environment, economy and energy for building retrofitting

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Building retrofitting plays a vital role in realising net-zero carbon ambition. Conventional retrofitting solutions are generally based upon decreasing operating energy usage or corresponding costs. However, many of these would increase the embodied carbon and energy. The innovation of this paper is to develop a building retrofitting assessment and optimisation approach to select the optimal combination of retrofitting options to minimise its carbon emissions, economic costs and energy usage over its life cycle. A real-life three-floor real-world office building is implemented to exhibit the behaviour of the newly developed retrofitting assessment and optimisation approach. This paper mainly focuses on passive options, including improving envelope thermal properties (e.g. wall insulations, roof insulations and triple-glazed windows) and installing renewable energy devices (e.g. photovoltaic panel, solar heater and wind turbine). The effects of varying embodied carbon, investment cost, embodied energy, annual salvage ratio, and material recycle ratio on the life cycle behaviour of the retrofitted building is investigated. For cost optimisation, the selection priority is sheep wool for roof insulation, insulation board for wall insulation, solar heater and wind turbine. The selection priority for energy or carbon optimisation would be insulation board for wall insulation, sheep wool for roof insulation, solar heater, triple-glazed window, and wind turbine. The largest achievable reduction in life cycle carbon, cost and energy are 3.9×10^{6} kg, £3.6×10^{5} and 7.8×10^{7} MJ, respectively. The research outcome will benefit the government for policymaking on approach-based net-zero retrofitting guidance and building engineers for designing sustainable retrofitting measures.

Keywords:
Life cycle optimisation; Retrofitting; Renewable energy; Net-zero building; Embodied carbon; Life cycle assessment

1. Background and research question

In 2018, the largest share of greenhouse gas emissions (i.e. 39%) and global primary energy usage (i.e. 36%) belonged to building construction and operation [1]. As 80% of buildings in 2050 have already been built [2], one of the major priorities should be decarbonising the existing stock through various building retrofitting measures. Building retrofitting is essential for decreasing greenhouse gas emissions and primary energy usage. Building envelope insulation can reduce its heating energy demand, while renewable energy devices can generate renewable energy production to supplement heating and electrical energy supply. Hence, one important research question is how to select retrofitting measures to achieve overall low greenhouse gas emissions, economic costs and energy usage of the retrofitted building during its entire life span. Therefore, the research aims to develop an assessment and optimisation approach to select the optimum combination of retrofitting measures to achieve the best life cycle performance. This paper begins with a discussion on background and research questions. It then follows with recent literature on office building retrofitting. The research methodology is presented in the third section, while the fourth section illustrates the case study. The research outcome is discussed in the fifth section. The sixth section summarises how to use the proposed approach in practical application, while the conclusion is presented in the last section.

2. Literature review of office building retrofitting approaches

A comprehensive literature review is conducted to investigate previous research works on office building retrofitting. After that, knowledge gaps are recognised while this study's novelty and contribution is formulated.

2.1 Previous research works

Many researchers have investigated the energy performance of various retrofitting measures on office buildings. Zhou et al. (2016) [3] examined the energy conservation capability and indoor environment quality of the retrofitted building using various envelope insulation materials and a ground-coupled heat pump. The physical model of the building is established for simulation via eQUEST. The retrofitting performance effect is evaluated by the year-round electricity consumption, thermal comfort, visual comfort, acoustics, and air quality. Costa et al. (2020) [4] proposed a guideline for transforming a four-floor office building into net-zero buildings in warm climates. The examined retrofitting measures include modifying external obstructions, changing the window-to-wall ratio, improving the solar heat gain factor of the glazed system, and adopting natural ventilation, while corresponding building energy consumption was simulated using EnergyPlus. The focus of this research is to balance electrical energy consumption with its supply, while the economic and life cycle performance is not evaluated. Gindi et al. (2017) [5] optimised the type, orientation and tilt angle of building-integrated PV panels to achieve maximum electricity production so as to decrease energy usage and carbon emissions of an office building. The renewable energy simulation software PVSOL was adopted to project energy production. Duran et al. (2021) [6] evaluated the improvement of energy efficiency and thermal comfort, as well as reduction of capital and running costs from the retrofitted office buildings using energy simulation software EnergyPlus. The investigated retrofitting strategies include daytime and night-time ventilation, as well as shading devices. In these pieces of literature, the energy-saving performance of single adoption of different retrofitting measures is explored using energy simulation results. The performance difference among various retrofitting measures is not mentioned, while no guideline is given on how to select the optimal retrofitting measures for a specific building.

Other researchers have evaluated the life cycle cost of various retrofitting measures on office buildings. Rabani *et al.* (2020) [7] adopted particle swarm optimisation (PSO) and generalised pattern search to select optimal retrofitting solutions to minimise a generic office building's life cycle cost. The thermal performance of the building is evaluated using IDA Indoor Climate and Energy, which is a dynamic energy simulation software. Meanwhile, the retrofitting options included supply air temperature, types of roof, external wall, floor, shading and windows. Shen *et al.* (2019) [8] compared the life cycle cost of a campus building with different retrofitting measures, including envelope insulation, air infiltration, natural ventilation, and renewable energy systems installation. The energy performance of each retrofitting measure is estimated using the SimBldPy modelling tool. Hong *et al.* (2021) [9] evaluated the life cycle cost of several types of low-rise office buildings with different retrofitting measures. IES-VE energy and environment simulation software is employed to assess the impacts of different retrofitting measures, including enhancing envelope insulation, adoption of energy-efficient lights and air conditioning systems, utilisation of solar PV and geothermal systems. Tokede *et al.* (2018) [10] evaluated the life cycle economic performance of retrofitting an office building with the consideration of revocability. The retrofitting options included insulation on the roof, external walls, floors, windows, and doors, as well as renewable energy devices. The retrofitting performance is evaluated using IES Virtual Environment (IES-VE) simulation software. Song *et al.* (2017) [11] investigated the life cycle economic performance of an office building in Southern China under different retrofitting measures. The energy performance under each retrofitting scenario is estimated using the TRNSYS simulation model. The retrofitting options include slightly improved and high-standard external wall insulation, infiltration rate and shading coefficient. Most of these research works focused on comparing the life cycle cost among different retrofitting measures. Although Rabani *et al.* (2020) [7] provided an optimisation approach for minimising life cycle cost, only building envelope materials and supply air temperature is considered as retrofitting options. Moreover, the optimisation is based upon the dynamic energy simulation of a generic office building, while the user perception and occupancy behaviour are not considered.

Another group of researchers have evaluated the energy usage and carbon emissions from various retrofitting measures during its entire life cycle. Gangolells *et al.* (2020) [12] identified the environmental, economic and energy impacts of some retrofitting measures on different types of office buildings during their life cycle. It was based upon the energy performance certificate scheme. It was found that the most efficient retrofitting measures included the replacement of heat pumps for heating and LEDs for lighting. Rabani *et al.* (2021) [13] evaluated the carbon emissions of a Norwegian office building under several different retrofitting options during its life cycle. The retrofitting measures include three air conditioning systems (electric boiler, district heating system and ground source heat pump), along with different envelope insulation materials. To assess life cycle total carbon, its embodied carbon is calculated using inventory software OneClick LCA while operating carbon emissions are estimated using energy simulation software IDA Indoor Climate and Energy. Asdrubali *et al.* (2019) [14] evaluated the payback time of a campus building under different retrofitting measures. Envelope insulation, solar collector, PV panel, ventilation system with heat recovery, and efficient lighting were considered as retrofitting options. The energy performance is evaluated using thermodynamic and first-principle thermodynamic models. Rodriguez *et al.* (2020) [15] assessed the life cycle carbon by improving office building's mechanical, electrical, plumbing parts. The environmental product declarations and public data sources are adopted as inventory databases. Silvestre *et al.* (2019) [16] evaluated the life cycle carbon of different envelope insulation materials for an office building. The retrofitted building's energy performance is evaluated using thermodynamic simulation, while embodied carbon is estimated using an inventory database. These research works mainly focused on assessing the energy usage and carbon emissions among different retrofitting measures during their life cycle, while no optimisation approach was provided to select the optimal combination of retrofitting measures to achieve life cycle optimal performance.

2.2 Knowledge gaps and contribution

As discussed above, the previous research works mainly focused on operating energy performance evaluation, life cycle inventory assessment of single adoption of different retrofitting measures. Only one research mentioned the life cycle cost optimisation among different retrofitting options. Therefore, the major knowledge gaps are recognised as follows:

- **Lack of life cycle carbon and energy optimisation**: The focus of previous research works [3-6] are mainly on operating energy consumption and carbon emissions. However, Schwartz et al. (2018) [17] points out that embodied, operating, and demolition carbon emissions account for 24%, 75% and 1% of the life cycle carbon footprint of the retrofitted building. Although there are some research works investigating the life cycle carbon of single adoption of certain retrofitting measures [12-16], there is no guiding approach to choose a combination of different retrofitting measures to minimise life cycle carbon emissions. Neither there is any research work considering the optimal trade-off between embodied and operating impacts of retrofitting materials.

- **Lack of real-life data**: First-principles and thermodynamic equations were generally used to derive the mathematical model of buildings through different simulation software, such as e-QUEST [3], EnergyPlus [4, 6], PVSOL [5], IDA-ICE [7, 13], SimBldPy [8], IES-VE [9, 10] and TRNSYS [11]. The thermal and electrical energy demand was estimated based on pre-determined building operating schedules. As no actual building energy performance was referred for comparison, these types of simulation might not be accurate to represent the user behaviour in real-world scenarios.
- **Lack of sensitivity evaluation**: The fixed value of retrofitting materials' inventory data (i.e. embodied carbon, investment cost and embodied energy) was generally adopted. However, the inventory carbon, cost and energy of the same material might be different due to various manufacturing processes. There is no study considering the effects of the varying embodied carbon, investment cost, embodied energy, annual salvage ratio, and material recycle ratio on the life cycle performance of retrofitted buildings.

This paper’s research aim is to design an assessment and optimisation strategy thus to select the optimal combination of retrofitting measures and achieve life cycle optimal economic, energy and environmental capability. The innovation and contribution of this paper are summarised as follows:

- **Life cycle carbon and energy optimisation:** To consider the optimisation over its whole life cycle, the trade-off between embodied carbon, investment cost and embodied energy against year-round greenhouse gas emissions reduction, operating cost-saving, energy consumption reduction would be investigated. Therefore, optimal retrofitting design combination of roof insulation, wall insulation, triple-glazed window, solar heater, wind turbine and PV panel will be selected in view of life cycle carbon reduction, cost-saving and energy reduction.
- **Real-life data for building energy performance evaluation:** Historical gas and electricity bills, current building properties and historical weather data will be adopted to evaluate the current and retrofitted building energy performance in a real-world situation, which also reflects the user behaviour. Meanwhile, investment costs from local supply chains, along with embodied energy and carbon information from the public national inventory database, will be adopted to assess the investment and embodied impacts of different retrofitting materials.
- **Implementation of sensitivity analysis:** As the embodied carbon, investment cost, embodied energy, material recycle ratio of the same retrofitting measure might be different due to various manufacturing processes, while the annual salvage ratio depends on the actual project. The effects of varying embodied carbon, investment cost, embodied energy, annual salvage ratio, and material recycle ratio on various retrofitting assessment criteria will be investigated. The retrofitting

assessment criteria include payback year of embodied carbon, investment cost and embodied energy, as well as life cycle payback carbon, cost and energy.

These three innovations and contributions are adopted as an effort to response the research question of how to select retrofitting measures to achieve overall low greenhouse gas emissions, economic costs and primary energy usage of the retrofitted building during its life cycle. As a result, this research aims to design an assessment and optimisation approach to select the optimal combination of retrofitting measures to achieve life cycle optimal performance, can be realised.

3. Research methodology

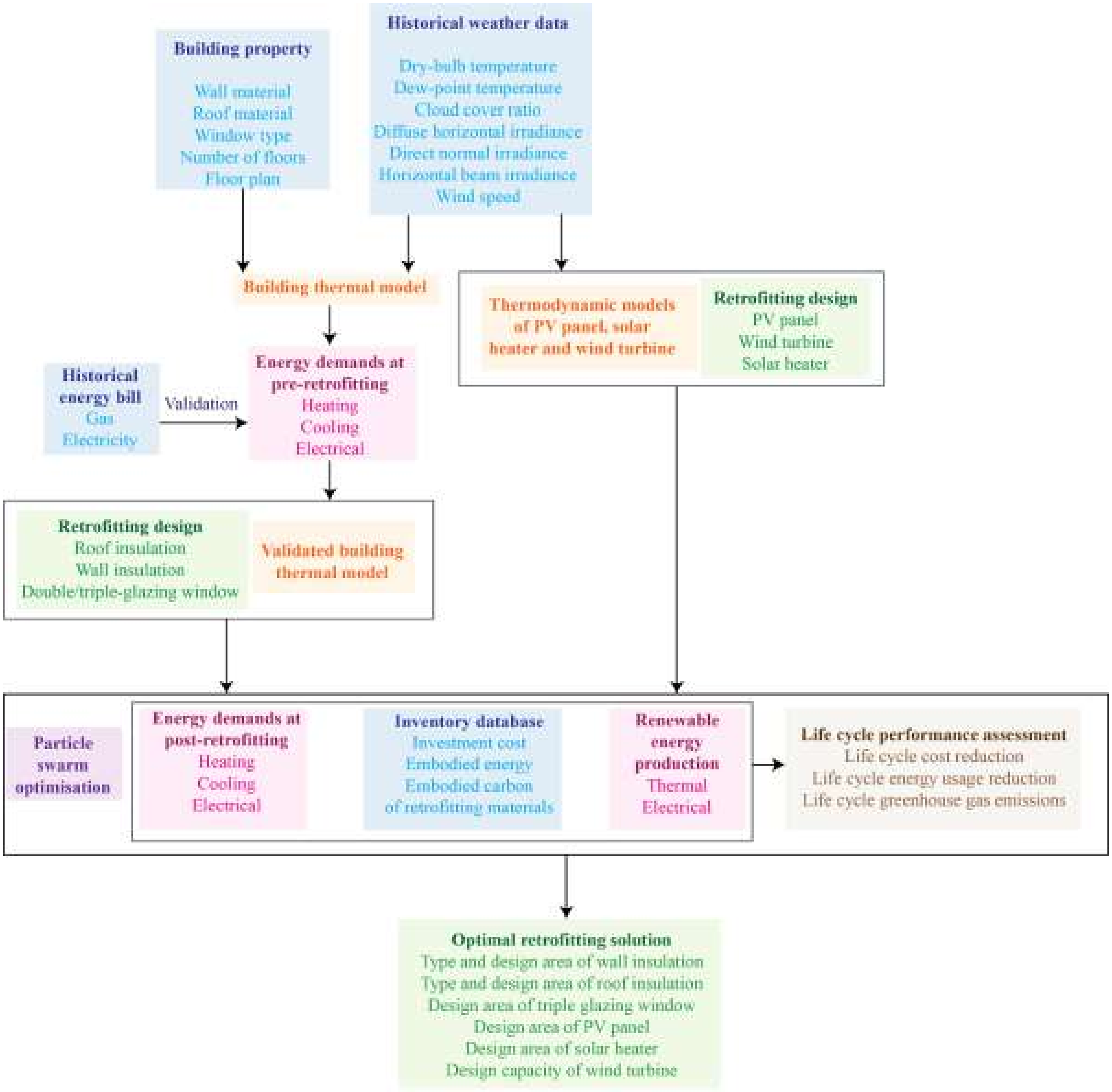

Fig. 1. Flowchart of proposed life cycle assessment and optimisation retrofitting approach.

As discussed in Section 1, this study's research aim is to propose a retrofitting optimisation approach to select retrofitting measures for office building while achieving life cycle minimum carbon, cost and energy. The flowchart of the proposed building retrofitting assessment and optimisation approach is shown in Fig. 1. The input information includes building property, weather data, energy bill and inventory database. The output information is the optimal combination of various retrofitting measures. The life cycle assessment and optimisation approach mainly consists of life cycle assessment criteria, life cycle optimisation module and mathematical models of building materials and renewable energy devices. The life cycle assessment criteria, life cycle optimisation module and corresponding mathematical models are discussed in Sections 3.1, 3.2 and 3.3, respectively. To illustrate the effectiveness of the developed assessment and optimisation approach, it is implemented on an office building in real life. Sensitivity analysis is implemented on the single adoption of each retrofitting option, as demonstrated in Section 4.1. After that, the trade-off between embodied and operating impacts of different retrofitting options is evaluated, as shown in Section 4.2. Finally, the life cycle performance of each obtained optimal retrofitting solution is investigated, as discussed in Section 4.3. Therefore, the effectiveness of the proposed assessment and optimisation approach can be evaluated, thus meeting the research question and objective raised in Section 1.

3.1 Life cycle assessment criteria

Life cycle assessment criteria mainly include carbon emissions, economic costs, and primary energy usage during its life cycle, along with payback year of embodied carbon, investment cost and embodied energy. The life cycle carbon emissions and energy usage include both embodied and operational impacts. The definition and boundary of the building life cycle are summarised in Table 1. The embodied impacts are determined by national inventory databases and environmental product declarations, while the operational impacts depend upon the actual energy demand for the building operating. In this study, the embodied impacts refer to the production stage (A1-A3), end-of-life stage (C1-C4) and benefits beyond the system boundary (D). However, the construction process stage (A4, A5) is excluded mainly owing to a lack of data and low contributions to the total primary energy usage and greenhouse gas. The operational impacts refer to parts of the use stage (B6.1-6.3). The maintenance, repair, replacement and refurbishment impacts are excluded since the retrofitted building's life span is considered as 20 years. Most of the retrofitting materials should last longer than 20 years. Thus no maintenance, repair, replacement or refurbishment is needed. Meanwhile, it is also because there is a lack of data for such impacts while their influence on the total energy usage and carbon emissions is low.

Table 1. Definition and boundary of the building life cycle [18].

Production	A1	Supply of raw material
	A2	Transportation
	A3	Manufacturing
Construction process	A4	Transportation
	A5	Construction and installation
Use	B1	Usage
	B2	Maintenance
	B3	Repairing
	B4	Replacement
	B5	Refurbishment
	B6.1	Building-related operating energy usage, regulated
	B6.2	Building-related operating energy usage, unregulated
	B6.3	User and use-related operating energy usage
	B7	Operating water usage
	B8	Building-induced mobility
End-of-life	C1	Deconstruction and Demolition
	C2	Transportation
	C3	Processing of waste
	C4	Disposal
Benefits and loads beyond the system boundary	D	Potential of reuse, recovery and recycling

Life cycle reduction of carbon emissions, cost-saving and energy usage depends on the decrease of carbon emissions, economic costs and energy usage at the post-retrofitting and pre-retrofitting stage.

$$\Delta LC_i = LC_{i,pre} - LC_{i,post} \qquad \text{Equation 1}$$

i = ca, co, or en, which refers to carbon emissions, economic costs and primary energy usage, respectively. At the pre-retrofitting stage, the life cycle carbon emissions $LC_{ca,pre}$, life cycle economic costs $LC_{co,pre}$ and life cycle energy $LC_{en,pre}$ is determined by total greenhouse gas emissions $B_{ca,pre}$, economic costs $B_{co,pre}$ and primary energy usage $B_{en,pre}$ during the use stage, respectively.

$$LC_{i,pre} = B_{i,pre} \qquad \text{Equation 2}$$

$$B_{i,pre} = b_{i,ng}\frac{Q_{pre,h}}{\eta_B} + b_{i,ele}Q_{pre,e} + b_{i,ele}\frac{Q_{pre,c}}{COP_{AC}} \qquad \text{Equation 3}$$

$Q_{pre,h}$, $Q_{pre,c}$ and $Q_{pre,e}$ is the heating, cooling and electrical energy demand at the pre-retrofitting stage; η_B and COP_{AC} refers to the efficiency of the gas boiler and coefficient of performance (COP) of air conditioning system. $b_{ca,ng}$, $b_{co,ng}$ and $b_{en,ng}$ are the equivalent greenhouse gas emissions, economic cost, and primary energy usage of unit consumption of natural gas, respectively. Meanwhile, $b_{ca,ele}$, $b_{co,ele}$ and $b_{en,ele}$ are the equivalent greenhouse gas emissions, economic cost, and primary energy usage of unit consumption of electricity, respectively.

At the post-retrofitting stage, life cycle carbon emissions $LC_{ca,post}$, life cycle economic costs $LC_{co,post}$ and life cycle energy usage $LC_{en,post}$ is determined by total greenhouse gas emissions $B_{ca,post}$, economic costs $B_{co,post}$, primary energy usage $B_{en,post}$ at the use stage, along with embodied carbon, investment cost and embodied energy of each retrofitting material at the production stage ($A_{ca,post}$, $A_{co,post}$, $A_{en,post}$), end-of-life stage ($C_{ca,post}$, $C_{co,post}$, $C_{en,post}$), and benefits beyond the system boundary ($D_{ca,post}$, $D_{co,post}$, $D_{en,post}$).

$$LC_{i,post} = A_{i,post} + B_{i,post} + C_{i,post} - D_{i,post} \qquad \text{Equation 4}$$

$$A_{i,post} = \sum_{j=0}^{j=N} a_{i,j}x_j \qquad \text{Equation 5}$$

$$B_{i,post} = b_{i,ng}\frac{Q_{post,h}}{\eta_B} + b_{i,ele}Q_{post,e} + b_{i,ele}\frac{Q_{post,c}}{COP_{AC}} \qquad \text{Equation 6}$$

$$C_{i,post} = \sum_{j=0}^{j=N} c_{i,j}x_j \qquad \text{Equation 7}$$

$$D_{i,post} = \sum_{j=0}^{j=N}(a_{i,j} + c_{i,j})x_jR_{i,j} \qquad \text{Equation 8}$$

j refers to the retrofitting measure, j = RI, WI, TW, PV, SH or WT, respectively, indicating roof insulation, wall insulation, triple-glazed window, PV panel, solar heater and wind turbine. *N* is the total number of retrofitting options. x_j refers to the design parameters of various retrofitting measures. $a_{i,j}$ and $c_{i,j}$ refers to the embodied impacts of each retrofitting measure at the production stage and end-of-life stage, respectively. For economic costs, $R_{co,j} = (1 - r_{sal})^{ls}$. r_{sal} is the annual salvage value rate, indicating the amount of an asset to be worth at the end of its lifespan. The annual salvage value rate is generally within the range of 5%-10%. If energy or carbon impacts, $R_{en,j} = R_{ca,j} = r_{rec,j}$. $r_{rec,j}$ is the recycle ratio of each retrofitting material at life cycle stage D. $Q_{post,h}$, $Q_{post,c}$ and $Q_{post,e}$ is the heating, cooling and electrical energy demand at post-retrofitting stage. The heating and cooling demand can be reduced due to the adoption of wall and roof insulation, triple-glazed window and solar heater. The actual electricity demand can be reduced by PV panels and the wind turbine. The heating and cooling demand at the pre-retrofitting and post-retrofitting stage ($Q_{pre,h}$, $Q_{pre,c}Q_{post,h}$, $Q_{post,c}$) is estimated to satisfy the thermal comfort of occupancy. Therefore, temperature set-points are 22°C and 25°C in winter and summer, respectively, while fresh air supply rate is 10L/s [19].

Payback year of embodied carbon Y_{ca}, investment cost Y_{co} and embodied energy Y_{en} indicates the ratio of net embodied carbon, investment cost and embodied energy against the year-round reduction of greenhouse gas emissions, economic costs and primary energy usage. It indicates the length of time during which the carbon, cost and energy generated at the material manufacturing stage can be compensated by its corresponding year-round carbon reduction, cost-saving and energy reduction during its life cycle.

$$Y_i = \frac{A_{i,post}+C_{i,post}-D_{i,post}}{B_{i,post}} \qquad \text{Equation 9}$$

3.2 *Life cycle optimisation module*

The function of the life cycle optimisation module is to select the optimal combination of retrofitting materials to achieve life cycle optimal environmental, economic or energy performance. It is conducted according to the energy performance of each retrofitting measure.

3.2.1. Decision variables and constraints

The retrofitting decision variables consist of roof insulation's type (y_1), roof insulation's design area (x_1), wall insulation's type (y_2), wall insulation's design area (x_2), triple-glazed window's design area (x_3), PV panel's design area (x_4), solar heater's design area (x_5), and wind turbine's design capacity (x_6). The wall insulation's design area, roof insulation's design area, triple-glazed window's design area should not exceed the overall external wall area (S_{wall}), overall roof area (S_{roof}) and window area (S_{win}), respectively. The solar heater and PV panel's total design area cannot exceed the overall roof area. As it is an on-site wind turbine, its design power cannot be larger than 1 kW. The design variables, along with their constraints, are summarised in Table 2.

Table 2. Retrofitting decision variables and constraints

Retrofitting option	Decision variables	Symbol	Units	Constraints
Roof insulation	Design area	x_1	m^2	$x_1 \leq S_{roof}$
	Type	y_1	-	-
Wall insulation	Design area	x_2	m^2	$x_2 \leq S_{wall}$
	Type	y_2	-	-
Triple glazed window	Design area	x_3	m^2	$x_3 \leq S_{win}$
PV panel	Design area	x_4	m^2	$x_4 + x_5 \leq S_{roof}$
Solar heater	Design area	x_5	m^2	
Wind turbine	Design capacity	x_6	kW	$x_6 \leq$ 1 kW

3.2.2 Optimisation objective and algorithm

The optimisation objectives include net reduction of life cycle cost from unit investment cost (NLC_{co}), net reduction of life cycle energy usage from unit embodied energy (NLC_{en}), and net reduction of life cycle carbon emissions from unit embodied carbon (NLC_{ca}).

$$NLC_i = \frac{\Delta LC_i}{A_{i,post}+C_{i,post}-D_{i,post}}$$ Equation 10

The mixed-discrete particle swarm optimisation (PSO) would be adopted to select the optimal design variables to maximise the optimisation objective (i.e. NLC_{cost}, NLC_{energy} and NLC_{carbon}). The design variables include continuous values (i.e. x_1-x_6) and discrete values (i.e. y_1 and y_2). Particle swarm optimisation algorithm would be adopted to select the optimal retrofitting solution thus optimise the life cycle retrofitting performance.

3.3 Mathematical model of building physics and renewable energy devices

The first principle-based building thermal model and thermodynamic models of renewable energy devices are developed to estimate the building energy performance of the current state as well as energy-saving potential after various retrofitting measures.

3.3.1. Building

Building thermal demand is determined by external and internal heat gains. External heat gain is mainly due to infiltration Q_{inf}, ventilation Q_{vent}, transmission Q_{trans}; as well as solar energy Q_{solar}. Internal heat gain is generated by office equipment Q_{eq}, occupants Q_o and lighting Q_l. The detailed calculation of each heat gain can be found in [20].

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if $Q_{inf} + Q_{vent} + Q_{solar} + Q_{trans} + Q_o + Q_l + Q_{eq} > 0$ then
    $Q_c = Q_{inf} + Q_{vent} + Q_{solar} + Q_{trans} + Q_o + Q_l + Q_{eq}$
fi
if $Q_{inf} + Q_{vent} + Q_{solar} + Q_{trans} + Q_o + Q_l + Q_{eq} < 0$ then
    $Q_h = Q_{inf} + Q_{vent} + Q_{solar} + Q_{trans} + Q_o + Q_l + Q_{eq}$
fi
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Along with building property information and historical weather data, historical thermal and electrical energy demand can be estimated. The estimated energy demand would be compared with the historical energy bills to validate the thermal building model. Thereafter, building energy performance after envelope up-gradation can be predicted.

3.3.2 PV panel

Electricity can be generated from PV panels using solar energy. The electricity generation rate depends on the global solar radiation and electrical efficiency of PV panels [21]. The polycrystalline solar panels are investigated in this study, while their design parameters are summarised in Table 3. The PV panel would be installed on the horizontal roof and be facing south. The year-round electricity production from PV panel at different inclination angles is summarised in Fig. 2; it is seen that the largest electricity production can be obtained when the inclination angle is 30°.

$$Q_{PV} = G \cdot x_4 \cdot \eta_{PV,n}[1 + \varepsilon_{PV,T}(T_{db} - T_{PV,ref})][1 + \varepsilon_{PV,G}(G - G_{PV,ref})] \qquad \text{Equation 11}$$

G refers to global solar radiation, while other parameters are summarised in Table 3.

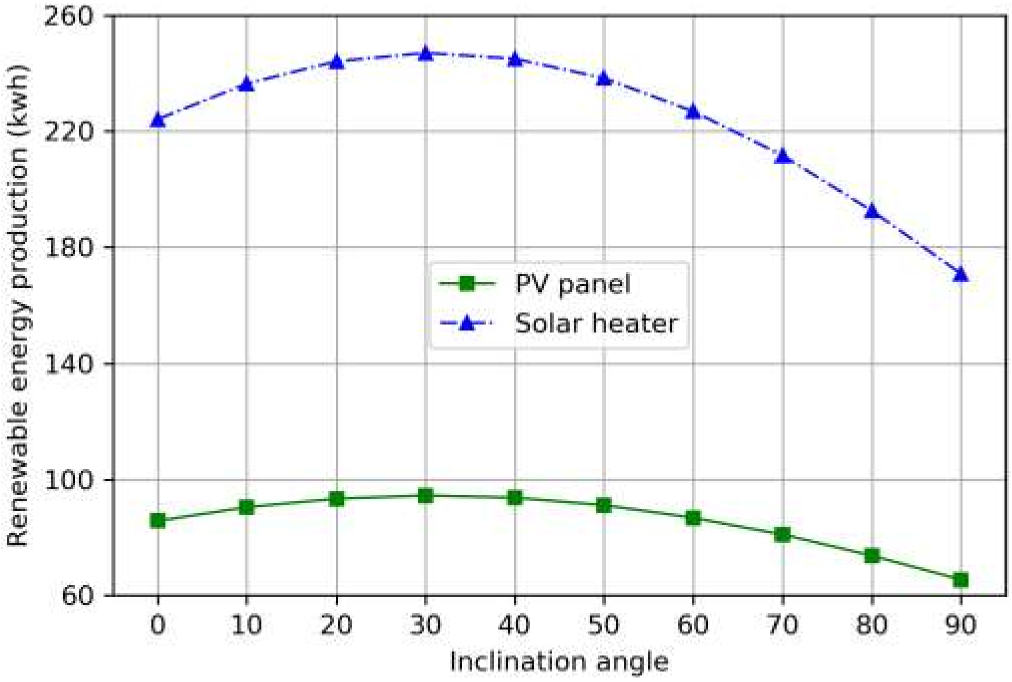


Fig. 2. Year-round renewable energy production at different inclination angles.

Table 3. Parameters of PV panel [21].

Design parameter	Symbol	Unit	Value
Nominal efficiency	$\eta_{PV,n}$	-	0.12
Reference PV temperature	$T_{PV,ref}$	K	298
Reference PV radiation	$G_{PV,ref}$	kW/ m^2	1
Coefficient of PV temperature	$\varepsilon_{PV,T}$	-	-5×10^{-3}
Coefficient of PV solar radiation	$\varepsilon_{PV,G}$	-	25×10^{-6}

3.3.3 Solar heater

Solar energy can be transformed into thermal energy by means of a solar heater [22]. The types of solar heaters consist of evacuated glass, flat plate and unglazed collectors [23]. The thermal efficiency of solar heater is affected by the refrigerant, while the common refrigerants include water, ammonia, carbon dioxide, ethane, ethylene etc [24]. Due to its popularity and low cost, a plate collector with water as a refrigerant is adopted in this study. The useful thermal energy generated by the solar heater can be calculated using Eq. 35 [25], while the design parameters are summarised in Table 4. Solar heater can also be installed on the horizontal roof and be facing south. The yearly thermal energy production from the solar heater at different inclination angles is also presented in Fig. 2. Thus, the largest thermal energy production can be obtained when the inclination angle is 30°.

$$Q_{SH} = G \cdot x_5 \cdot \eta_{SH,n} \left[1 + \varepsilon_{SH,1} \frac{T_{DB} - T_{SH,ref}}{\left(\frac{G}{G_{SH,ref}} \right)} + \varepsilon_{SH,2} \left(\frac{T_{DB} - T_{SH,ref}}{\left(\frac{G}{G_{SH,ref}} \right)} \right)^2 \right] \qquad \text{Equation 12}$$

Table 4. Parameters of solar heater [18].

Design parameter	Symbol	Unit	Value
Nominal efficiency	$\eta_{SH,n}$	%	70
Reference solar heater temperature	$T_{SH,ref}$	K	298
Reference solar heater radiation	$G_{SH,ref}$	kW/ m^2	1
Correction coefficient of temperature	$\varepsilon_{SH,1}$	-	5.6
Correction coefficient of solar radiation	$\varepsilon_{SH,2}$	-	8.7

3.3.4 Wind turbine

Electrical power can be produced from wind turbines using wind sources. The electricity generation rate depends on wind speed. The wind turbine manufactured by Eoltec is adopted in this study. The key parameters of the wind turbine are summarised in Table 5. Meanwhile, the correlation between operating capacity and wind speed can be found from the performance curve of the wind turbine, as shown in Fig. 3.

Table 5. Parameters of wind turbine [26].

Parameters	Unit	Value
Nominal power	kW	1
Maximum desgin wind speed	m/s	12
Cut-in wind speed	m/s	4
Maximum	rpm	245
Number of blades	-	2

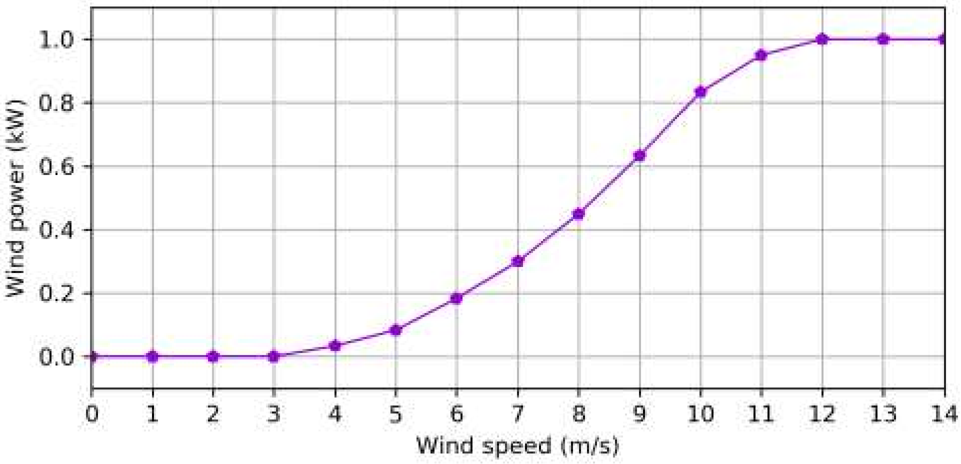


Fig. 3. The performance curve of the wind turbine.

4 Real-world building implementation

An office building in real life is implemented to investigate the retrofitting behaviour obtained by the proposed optimisation approach. The general building information, TRNSYS simulation model, energy performance of envelope up-gradation and renewable energy production are introduced in this section. The manufacturing and construction activities are assumed to occur in the United Kingdom, while all inventory data is collected from the current market and supply chain in the United Kingdom.

4.1 Basic building information

The case study is based on Costain House, which is a characteristic medium-sized office building in the United Kingdom. It is a 3-storey office building located at Maidenhead. Its real architectural floor plan is illustrated in Fig. 4, while a perspective of this office building is presented in Fig. 5. The two glazed walls are facing north and east, respectively. The roof is horizontal, while there is no shading by adjacent buildings. At the current building, gas heater and electric chiller are adopted to provide heating and cooling energy, respectively. Other important building information is summarised in Table 6. For this office building, monthly gas and electricity consumption can be estimated through monthly gas and electricity bills in 2018. Meanwhile, the building electricity consumption is also recorded using the building management system.

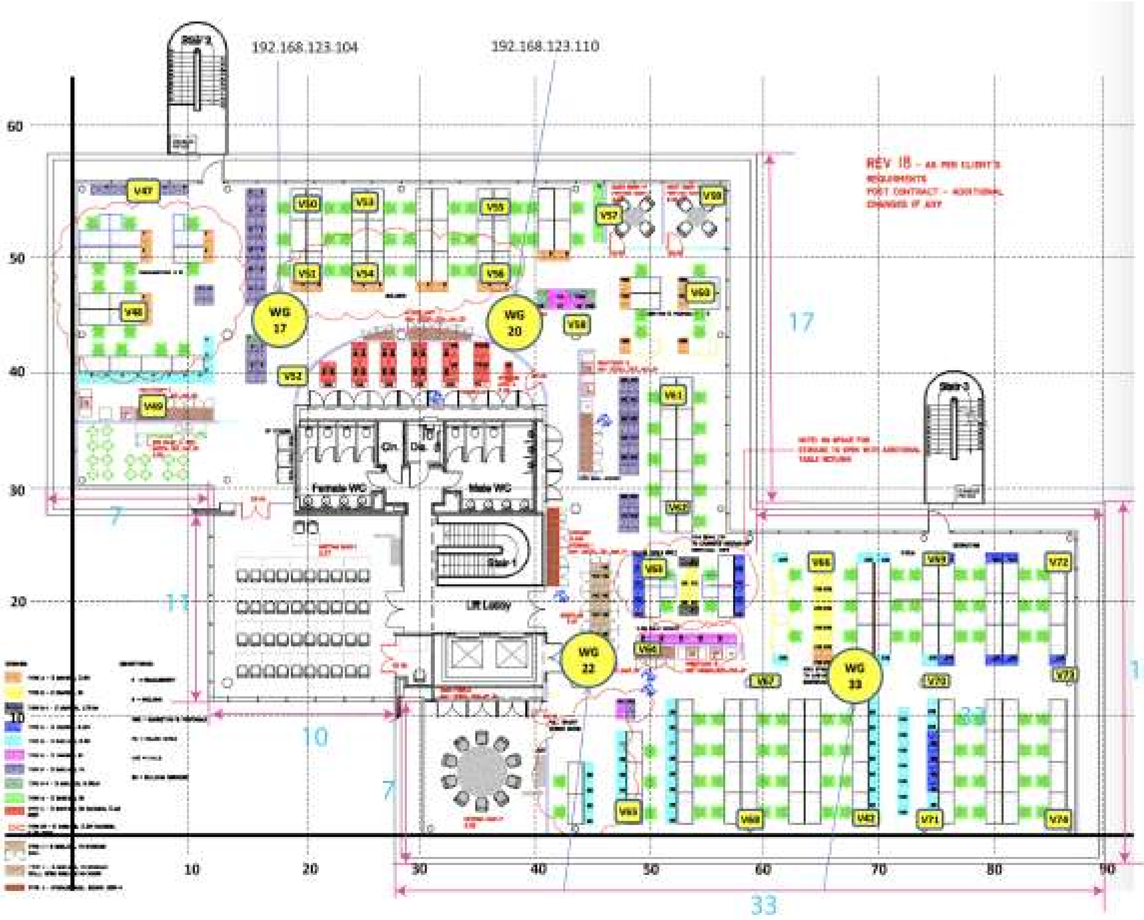


Fig. 4. Real architectural floor plan of Costain House.

Fig. 5. A perspective of Costain House.

Table 6. Building information of Costain House.

Design items	Unit	Value
Overall surface area of external wall	m^2	1499
Overall surface area of window	m^2	1008
Overall surface area of roof	m^2	604.8
Yearly gas consumption (2018)	kWh/m^2	128
Yearly electricity consumption (2018)	kWh/m^2	226
Occupancy density	m^2/persons	7.56
Occupancy heat gain	kW/person	0.15
Infiltration rate	ACH	0.3
Hot drinking water	L/h/person	2
Design indoor temperature in winter	°C	24
Design indoor temperature in summer	°C	26
Efficiency of existing gas boiler	%	80
COP of existing air conditioner	-	4

4.2 *TRNSYS system simulation model*

TRNSYS18 [27] is adopted to investigate the change of thermal energy demands through envelope up-gradation and energy production from renewable energy devices. The year-round weather profile documented at Maidenhead in 2018 is implemented as input parameters of the TRNSYS system simulation model. The weather profile includes humidity ratio, the temperature of dry-bulb air, cloud percentage, solar irradiance, ambient pressure and wind speed.

System components in the TRNSYS environment for the proposed study is shown in Fig. 6. Data reader, Type 9, is adopted to process the historical weather profile obtained from weather reports websites. Psychometrics, Type 33d, is adopted to interpret dew-point temperature into relative humidity so that it can be used in the thermal building model (i.e. Type 56). Solar radiation processor, Type 16, is adopted to obtain the total radiation, beam radiation, sky diffuse and incidence angle at different directions. Type 56 is adopted to estimate building thermal energy demands using the first principle models described in Section 4.1. To represent the real-world situation, the internal heat gains are set proportional to the electricity consumption. Meanwhile, the PV panel, solar heater and wind turbine are simulated using Type 103a, Type 73 and Type 90, respectively. Based on the input year-round weather profile, renewable energy production from these three energy devices can be estimated.

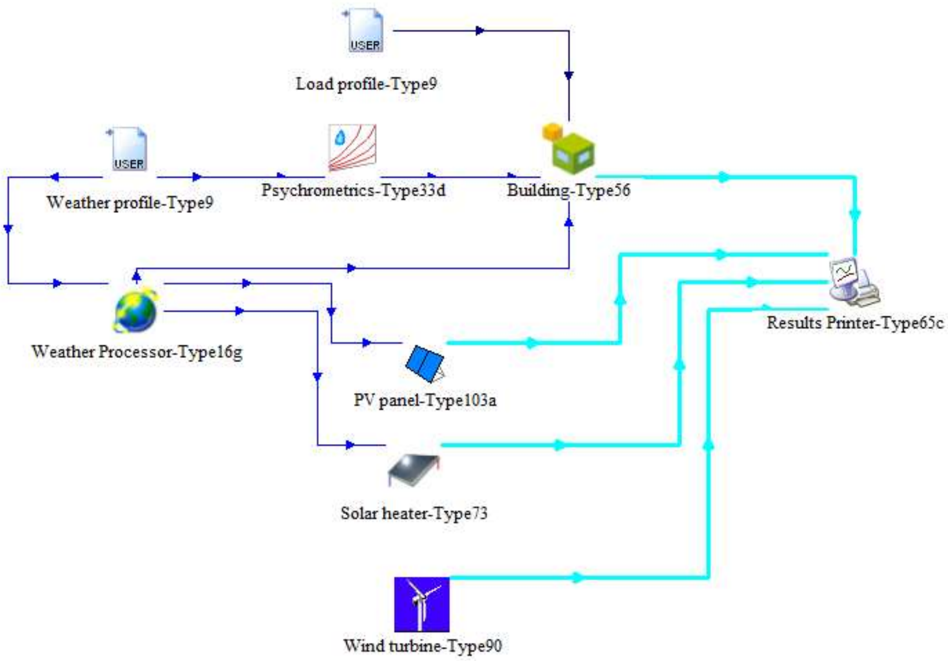


Fig. 6. Diagram of TRNSYS system simulation model.

To have a better understanding of the actual building operation and energy consumption, a workshop has been held with several building facility managers. According to their description, there exists a significant fraction of natural gas consumed by the kitchen on the ground floor and the hot drinking water services on three floors. During June and July, the outdoor air temperature is relatively high; thus, space heating is not required. Therefore, the actual gas consumption during these two months can be considered entirely owing to kitchen usage and hot drinking water. In other months, the gas consumption for kitchen usage and hot drinking water is assumed to be the same as those in June and July.

To validate the TRNSYS system simulation model, monthly natural gas consumption from the simulation result is compared to that from the actual natural gas bill of 2018. As shown in Fig. 7, the year-round mean absolute percentage error between the simulation and real value is 16.7%. The relatively larger simulation error of certain months may be due to the different operating schedules of the kitchen during some days. However, since this study focuses on the heating demand performance from building envelopes, the inaccurate results of kitchen and hot drinking water heating demands would not affect the simulation outcome. Therefore, the developed TRNSYS system simulation model is deemed validated.

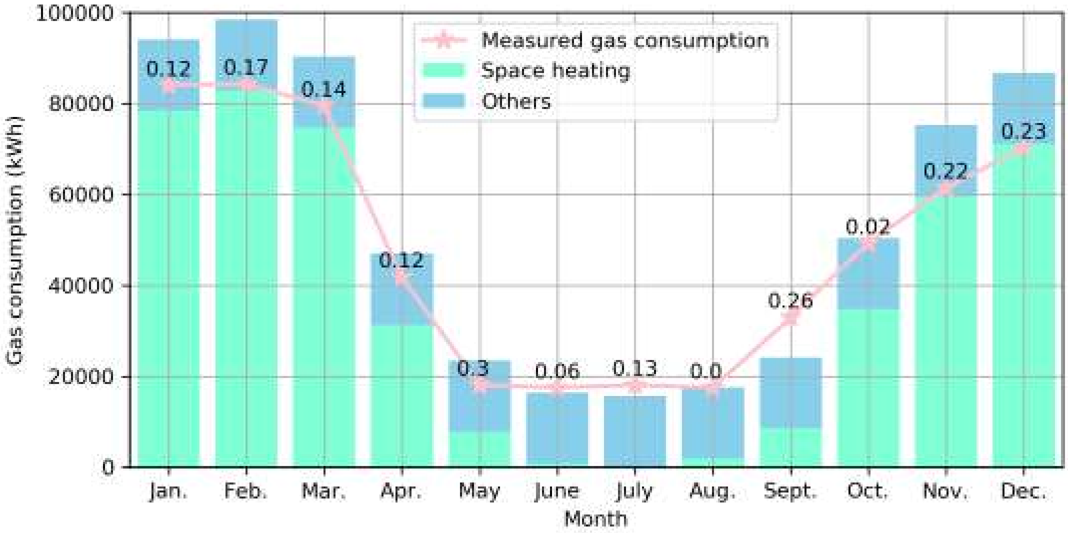
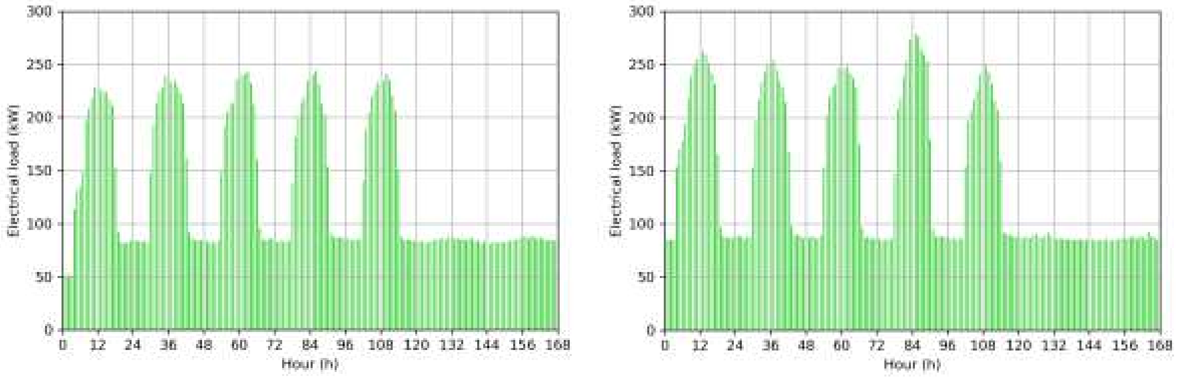
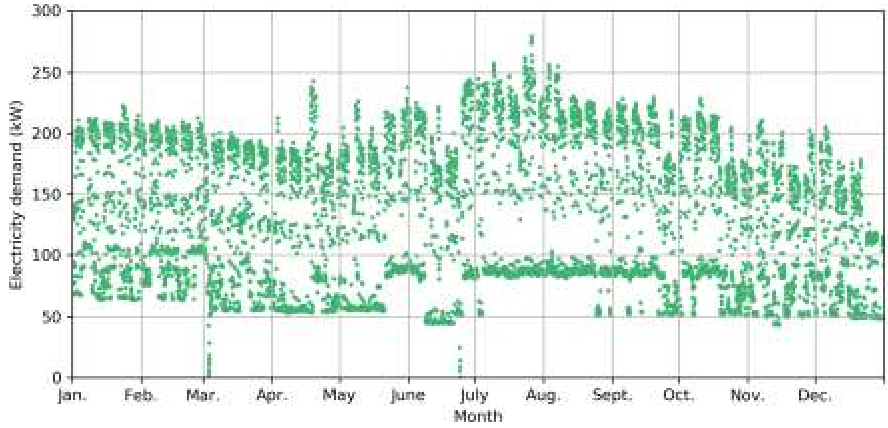


Fig. 7. Comparison of measured and simulated monthly gas consumption.

The actual half-hourly recorded electrical power consumption rate is presented in Fig. 8, while the thermal energy demands from simulation results are summarised in Fig. 9 and 10, respectively. The electricity consumption refers to actual electricity consumption for office equipment (i.e. computing servers, laptops, printers, lifts, etc) and air conditioning systems. The actual electricity consumption also reflects the occupancy behaviour in energy usage. In winter, the basic and peak electrical load is around 85 kW and 240 kW, respectively. In summer, the basic and peak electrical power consumption rate is approximately 110 kW and 200 kW, respectively. The electrical energy consumption in summer is larger than that in winter, owing to the electrical energy consumption of the air conditioning for satisfying cooling demand. The peak cooling and heating demands are 162kW and 300 kW, respectively. In winter, transmission heat gain occupies the biggest part of the building heating demand, and it is because of the large temperature difference between indoor and outdoor air. In contrast, solar and internal heat gain can help decrease heating demand. In summer, solar heat gain is the biggest contributor to cooling demand. On the contrary, transmission and ventilation heat gain can help reduce cooling demand since the dry-bulb temperature of outdoor air is smaller than that of indoor air.

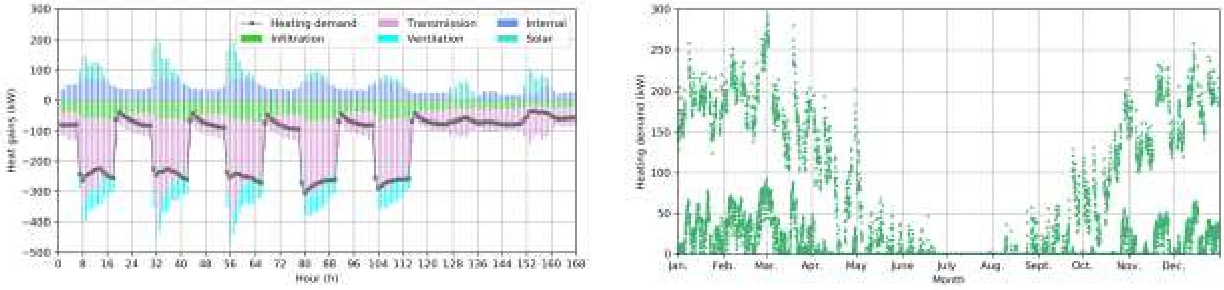


(a) The selected week in winter (b) The selected week in summer



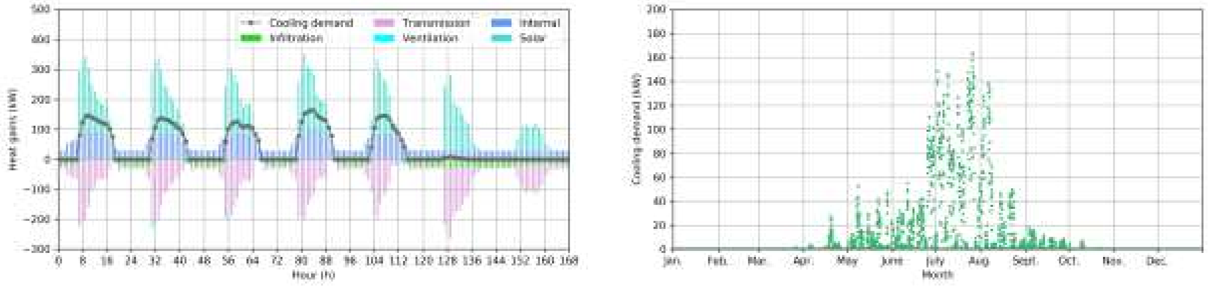
(c) Year-round

Fig. 8. Measured electrical power demand.



(a) The selected week in winter (b) Year-round

Fig. 9. Heating demand rate.



(a) The selected week in summer (b) Year-round

Fig. 10. Cooling demand rate.

4.3 Performance evaluation of building envelope up-gradation

The original roof of the office building is made up of concrete, with a thickness of 50 cm and a U-value of 2.45 W/(m^2·K). Market-available sheep wool and insulation boards with different thicknesses are adopted for roof insulation. The information on roof insulation materials is summarised in Table 7. The thickness, density, conductivity, U-value and price of each sheep wool are obtained according to the manufacturing information from the supply chain. It is seen that lower thickness results in a higher overall U-value while the lower unit price for both sheep wool and insulation boards. The embodied carbon and energy depends on the weight of the material, while the embodied energy and carbon in sheep wool is higher than that in wood-fibre insulation boards.

Table 7. Information on roof insulation materials.

Type	No	Thickness (cm)	Density (kg/m^3)	Thermal conductivity (W/m·K)	U-value (W/m^2·K)	Price (£/m2) [28]	Embodied energy [29, 30] (MJ/kg)	Embodied carbon [29, 30] (kg/kg)
Original	0	0	-	-	2.450	-	-	-
Sheep wool	1	15	14	0.042	0.251	19.2	46.5	43.9
	2	15	20	0.0359	0.218	27.9		
	3	10	20	0.0359	0.313	18.6		
	4	7.5	18	0.039	0.456	6.8		
Wood-fibre insulation boards	1	14	110	0.038	0.244	29.4	13.0	0.61
	2	12			0.280	21.4		
	3	8			0.398	14.9		
	4	6			0.503	12.0		
	5	4			0.685	9.8		

Table 8. Information of wall insulation materials.

No	Type	Thickness (cm)	Density (kg/m^3)	Conductivity (W/mK)	U-value (W/m^2K)	Price [28] (£/m^2)	Embodied energy [29] (MJ/kg)	Embodied carbon [29] (kg/kg)
0	No insulation	0	-	-	2.450	-	-	-
1	External wall insulation board	7	50	0.02	0.256	24.5	20.0	0.98
2		6		0.02	0.293	20.9		
3		5		0.02	0.344	18.0		
4		2		0.023	0.783	10.5		

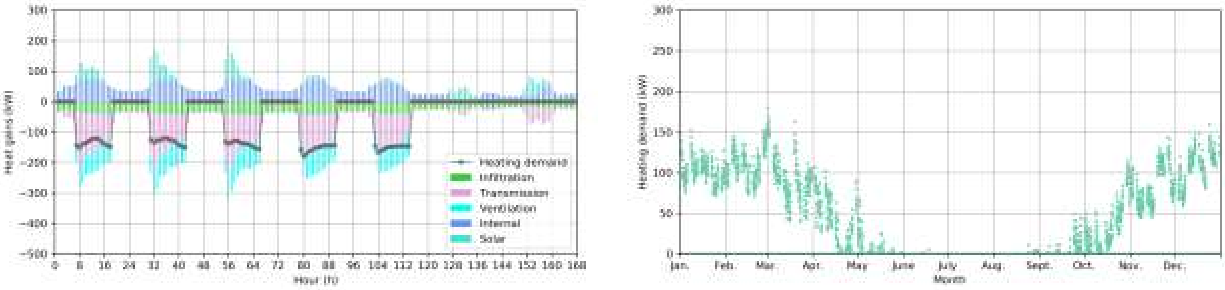
The original wall of the office building is constructed using concrete, with a thickness of 5 cm and a U-value of 2.45 W/(m^2·K). To investigate the effects of insulation on external wall, insulation boards with different thicknesses are studied. The information on wall insulation materials is summarised in Table 8. It is seen that lower thickness results in a higher overall U-value while lower unit price. The embodied energy and carbon depend on the weight of the material.

Since the office building is already installed with a double-glazed window, the triple-glazed window is considered as the retrofitting option. The U-value, price, embodied energy and embodied carbon of triple-glazed window is summarised in Table 9.

Table 9. Information about triple-glazed windows.

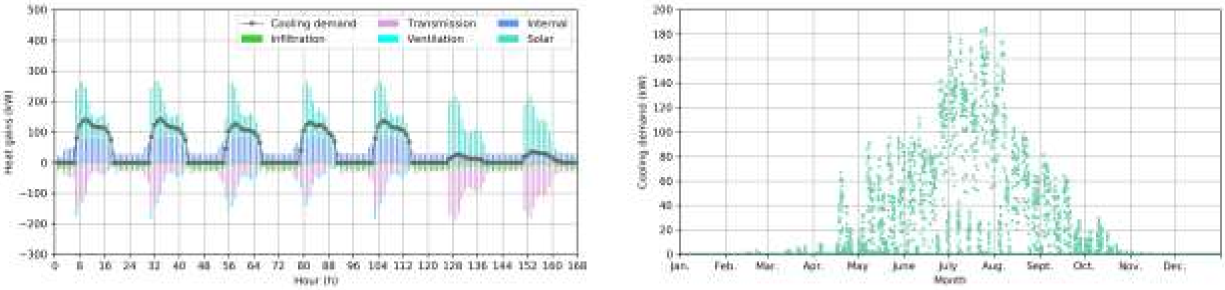
No	Type	Density (kg/m^3)	U-value (W/m^2K)	Price (£/m^2) [31]	Embodied energy [32] (kWh/m^2)	Embodied carbon [33] (kg/m^2)
0	Double-glazed	-	1.69	-	-	-
1	Triple-glazed	14	0.52	295	230	61

Assuming the roof is insulated by the sheep wool with the thickness of 75 mm, the wall is insulated by the insulation board with the thickness of 20mm, while all the double-glazed windows are replaced with the triple-glazed ones, the heating and cooling demand at the post-retrofitting stage is summarised in Figs.11 and 12, respectively. By adding insulation to the entire wall and roof area, the peak heating can be reduced to 180 kW while the peak cooling demand is increased to 186 kW, respectively. The slight increase in cooling demand is caused by the relatively lower transmission heat gain, thus higher cooling demand.



(a) The selected week in winter (b) Year-round

Fig. 11. Heating demand after retrofitting with envelop retrofitting.

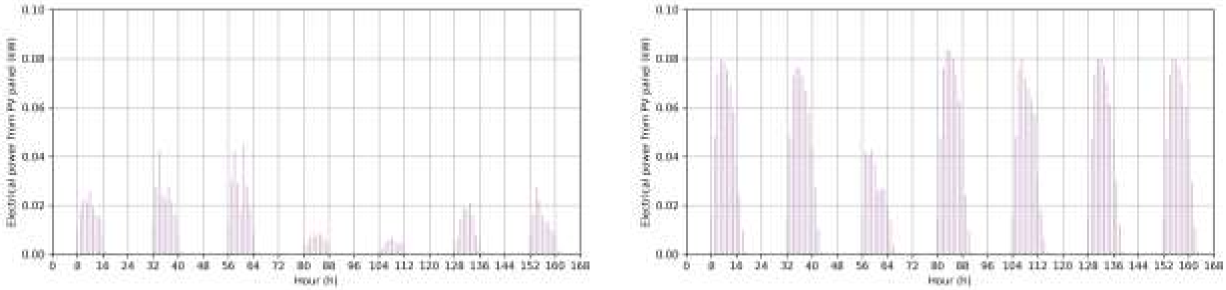


(a) The selected week in summer (b) Year-round

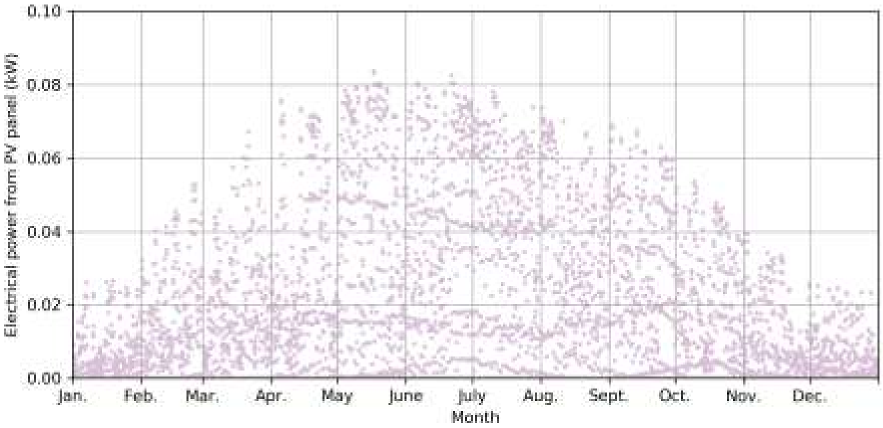
Fig. 12. Heating demand after retrofitting with envelop retrofitting.

4.4 Energy production from renewable energy devices

Weather profile of 2018 is adopted to estimate renewable energy production from PV panel, wind turbine and solar heater. The weekly and yearly energy production from PV panel (1 m^2), wind turbine (1 kW) and solar heater (1 m^2) are shown in Figs 13, 14 and 15, respectively. The design parameters of each renewable energy equipment are summarised in Table 10. By installing PV panel on the entire roof, or solar heater on the entire roof, or 1 kW wind turbine, the peak and yearly total energy production from PV panel, wind turbine and solar heater are summarised in Table 8. Due to larger solar radiation in summer, larger thermal and electrical energy can be produced from solar heater and PV panel.

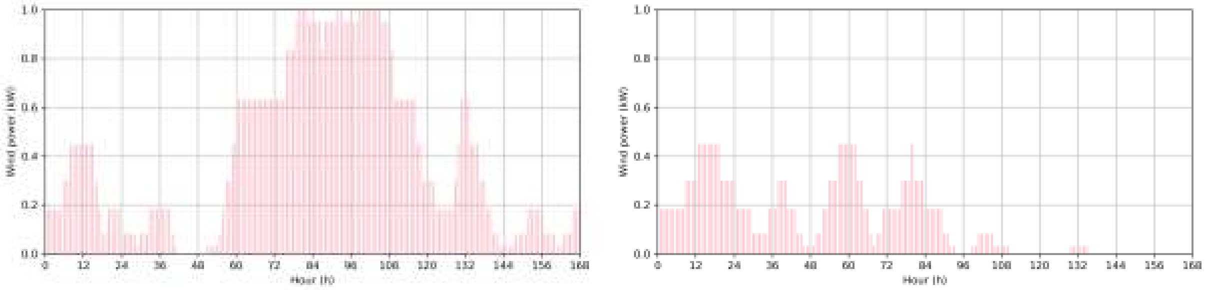


(a) The selected week in winter (b) The selected week in summer

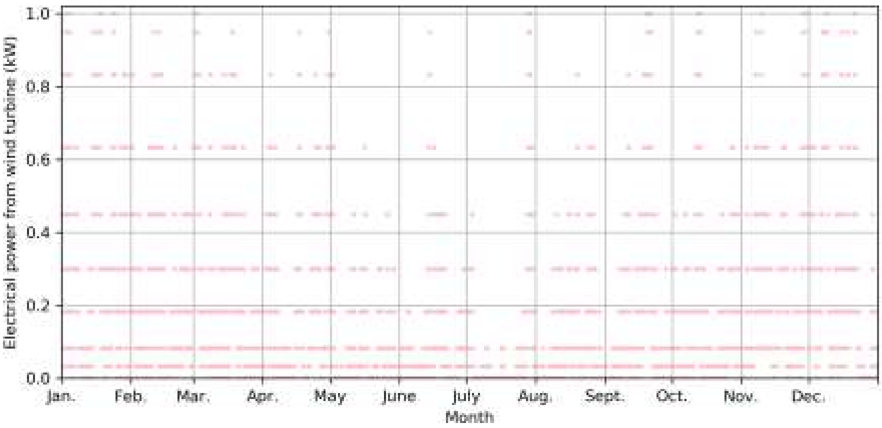


(c) Year-round

Fig. 13. Electrical power from PV panel.

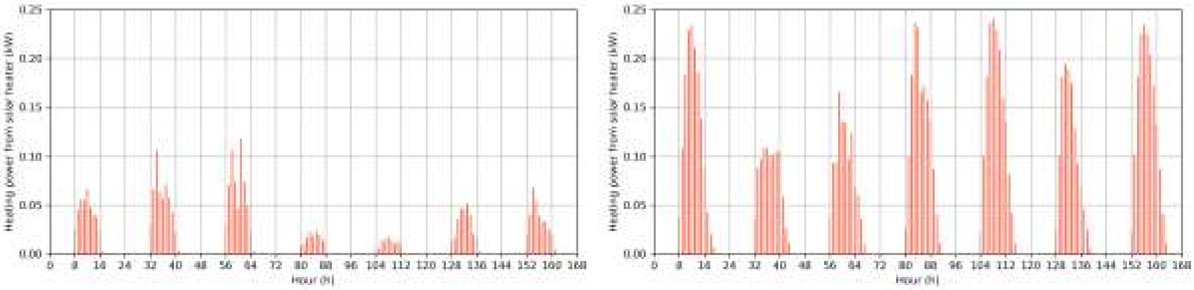


(a) The selected week in winter (b) The selected week in summer

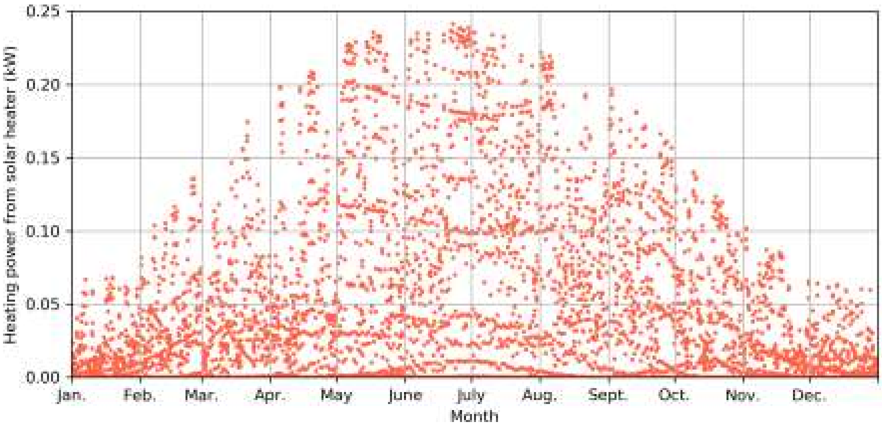


(c) Year-round

Fig. 14. Electrical power from wind turbine.



(a) The selected week in winter (b) The selected week in summer



(c) Year-round

Fig. 15. Thermal energy production rate of solar heater.

Table 10. Peak and yearly energy production and demand.

Energy type		Peak	Yearly energy
		kW	kWh
Renewable energy production	PV panel	0.0838	94.52
	Solar heater	0.2413	247.04
	Wind turbine	1	1501
Energy demand	Current heating demand	305	361528
	Heating demand after envelope upgradation	180	149464
	Current cooling demand	164	40785
	Cooling demand after envelope upgradation	186	94784

The inventory data of renewable energy devices, including PV panel, wind turbine and the solar heater is collected from various supply chains and databases in the UK, as summarised in Table 11.

Table 11. Inventory data for renewable energy devices.

Energy devices	Unit	Embodied carbon (kg)	Cost (£)	Embodied energy (MJ)
PV panel [34, 35]	m^2	157.8	219	3266.6
Wind turbine [36, 37]	kW	3487.7	83050	555666.7
Solar heater [38, 39]	m^2	240	38	3000

In addition, the inventory data of unit electricity and natural gas production is obtained to estimate the equivalent carbon emissions, economic costs and energy usage of building energy system, as summarised in Table 12.

Table 12. Inventory data of renewable energy devices.

Energy sources	Unit	Cost (£)	Embodied energy (MJ)	Embodied carbon (kg)
Power grid electricity [40, 41]	kWh	0.1310	8.86	0.21233
Natural gas [40, 42]	kWh	0.0211	3.6	0.18316

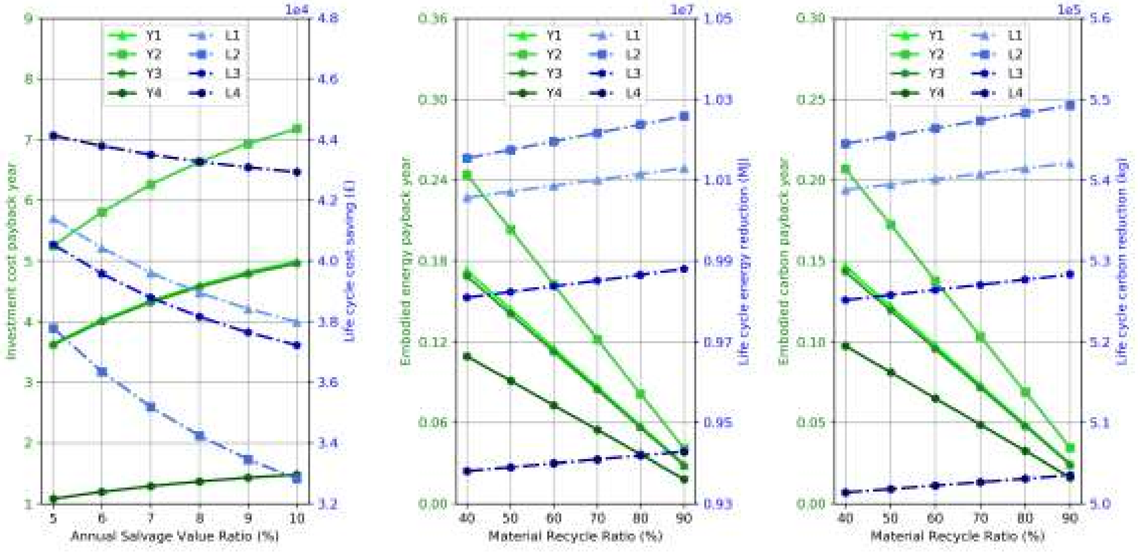
5 Results and discussion

In this section, sensitivity analysis of each retrofitting option, life cycle assessment of different retrofitting options, and retrofitting optimisation results are discussed.

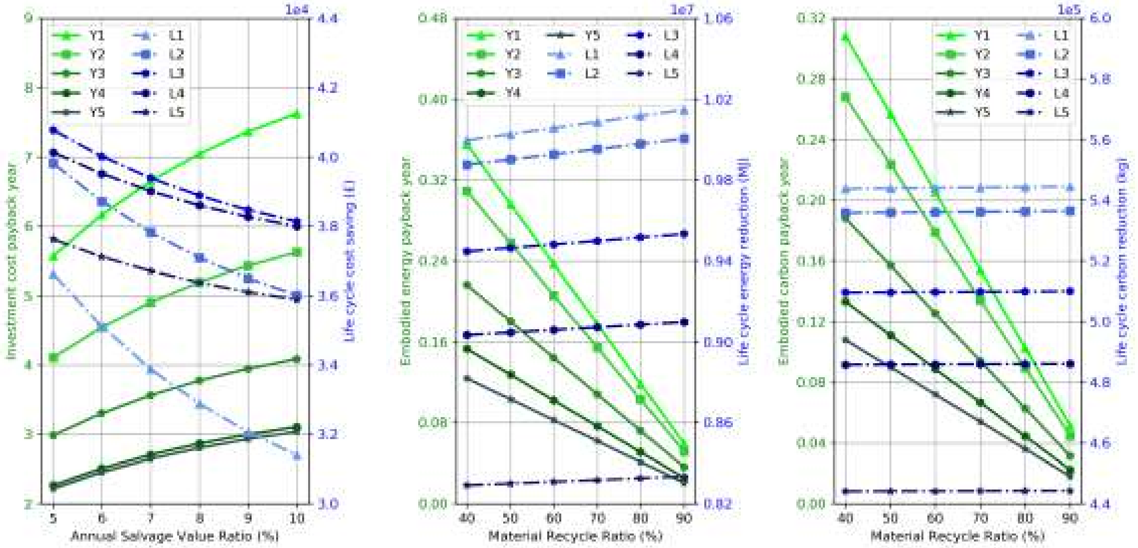
5.1 Sensitivity analysis of each retrofitting option

The effects of the annual salvage value ratio, material recycle ratio, varying embodied carbon, investment cost, embodied energy on the life cycle performance are investigated. The payback year and life cycle reduction of carbon emissions, economic costs and primary energy usage is summarised in Fig. 16. The shadow indicates the 10% variation of payback year and life cycle reduction due to the sensitivity variation in embodied carbon, investment cost and embodied energy.

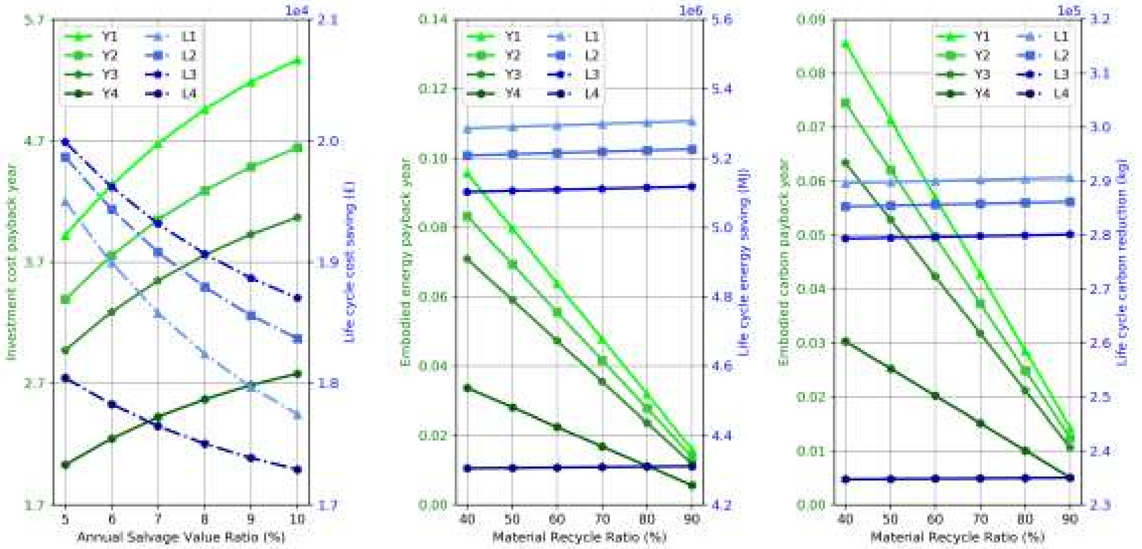
For different retrofitting measures, the larger annual salvage value rate indicates a higher investment cost degradation rate of the retrofitting materials. Thus, the payback year of investment cost increases while life cycle cost saving declines with the increase of the annual salvage value rate. On the contrary, the larger material recycle ratio indicates that more embodied energy and carbon can be reutilised at the end-of-life stage. As a result, the payback year of embodied energy and carbon decreases with the rise of material recycle ratio, while the reduction of carbon emissions and energy usage during its life cycle increases with the increase of recycle ratio. Therefore, in practical application, it is important for manufacturing companies and local supply chains to decrease the annual salvage ratio and increase material recycle ratio.



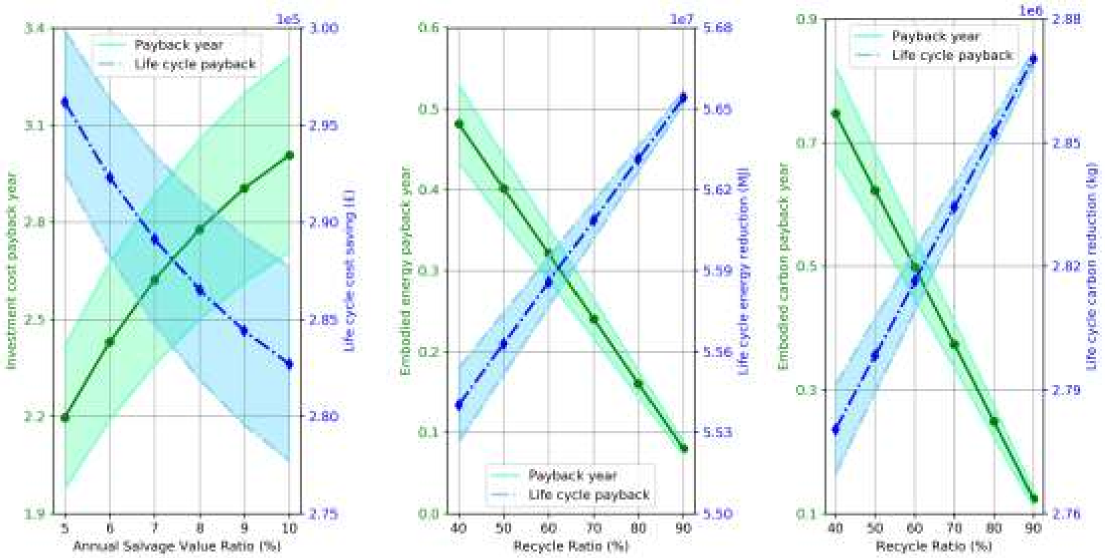
(a) Sheep wool for Roof insulation



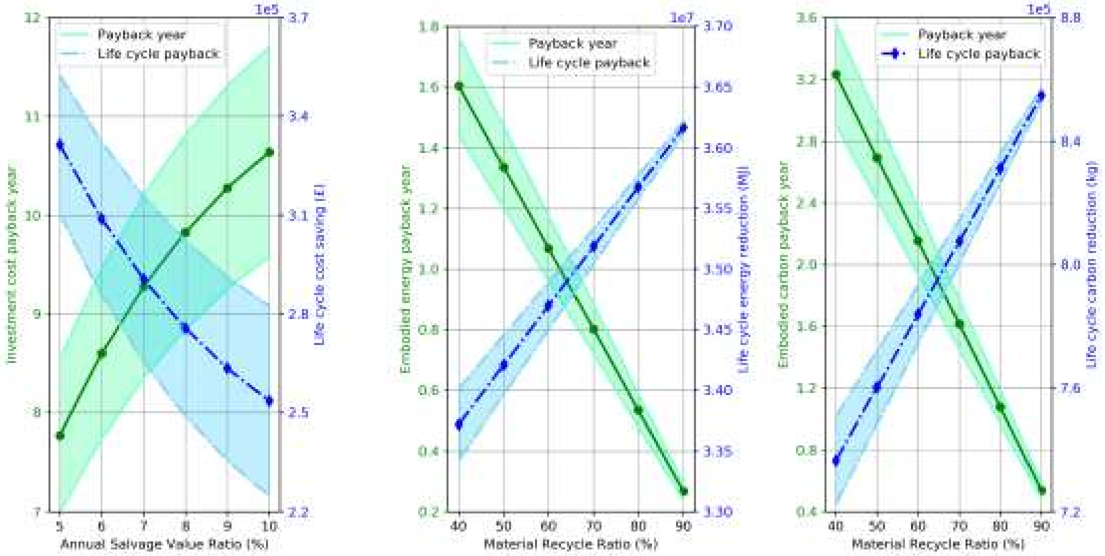
(b) Wood-fibre insulation boards for roof insulation



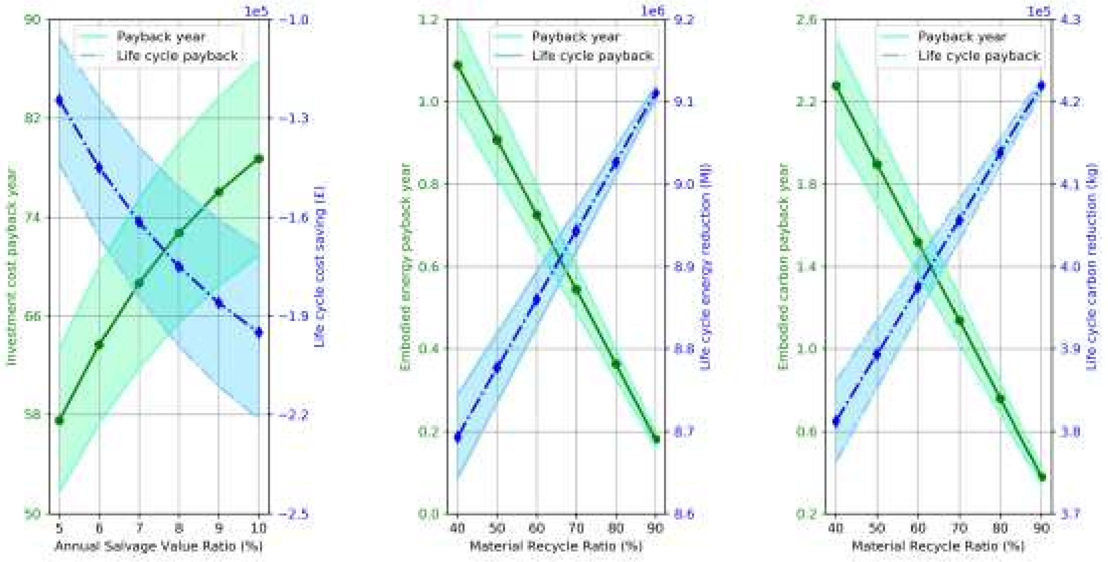
(c) External wall insulation board



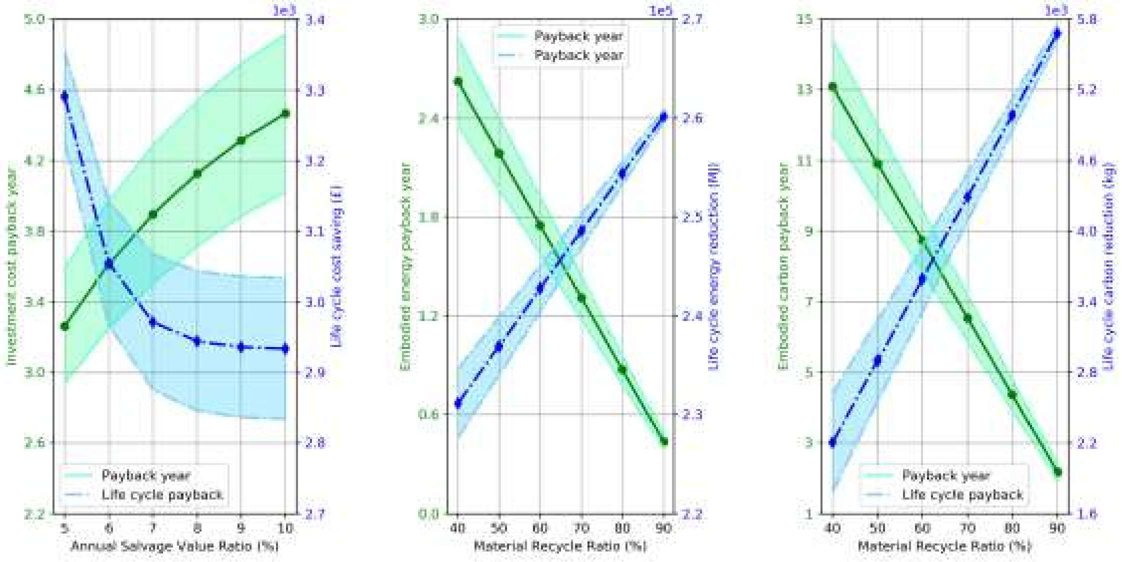
(d) Solar heater



(e) PV panel



(f) Triple-glazed window



(g) Wind turbine

Fig. 16. Life cycle assessment of each retrofitting material

For roof and wall insulation, the optimal life cycle reduction of carbon emissions, economic costs and primary energy usage, along with corresponding payback year, is identified from different material properties:

- The payback year of investment cost decreases while the life cycle cost saving increases with the decrease of the thickness of each insulation material. Therefore, the 7.5 cm sheep wool, 4 cm wood-fibre insulation board, and the 2 cm external wall insulation board result in the best economic performance.
- The payback year of embodied energy/carbon, as well as the life cycle energy/carbon reduction, decreases with the decrease of the thickness of each insulation material. As a result, 7.5 cm sheep wool, 4 cm wood-fibre insulation board, and 20 mm external wall insulation board has the smallest payback year of embodied energy and embodied carbon. On the contrary, 15 cm sheep wool, 14 cm

wood-fibre insulation board, and 7 cm external wall insulation board result in the highest energy and carbon reduction during its life cycle.

This indicates that the increase of insulation thickness does not necessarily mean better life cycle performance as it would increase embodied carbon, investment cost and embodied energy.

With the variation of embodied carbon, investment cost and embodied energy of each material, there exists a variation in payback year and life cycle performance for triple-glazed windows, PV panel, solar heater and wind turbine. The variation range of payback year of investment cost and life cycle economic cost saving increases with the increase of annual salvage ratio. Moreover, the variation range of payback year of embodied energy and carbon, as well as reduction of energy usage and carbon emissions along life cycle, declines with the increase of material recycle ratio. It indicates that it is vital to decrease embodied carbon, investment cost and embodied energy during the material manufacturing process.

5.2 Life cycle assessment of different retrofitting options

Figs. 17-19 are adopted to explore the trade-off between investment cost and operating year-round cost-saving, embodied energy and year-round operating energy consumption reduction, as well as embodied carbon and year-round greenhouse gas emissions reduction, respectively. In Figs. 17-19, the roof insulation area, wall insulation area and the triple-glazed window are kept at 100 m^2. It is seen that a higher year-round reduction in economic cost, primary energy usage and greenhouse gas emissions does not necessarily lead to overall better life cycle performance.

- From the economy point of view, both year-round cost-saving and investment cost decreases with the decrease of thickness for each type of insulation material. As a result, the external wall insulation board with a thickness of 2 cm and the sheep wool with a thickness of 7.5 cm are found to have the smallest payback year of investment cost and largest net life cycle cost saving per investment cost. Moreover, although the year-round cost saving of wind turbine is smaller than that of PV panel, the wind turbine has better life cycle performance, such as smaller payback year of investment cost and larger net life cycle cost saving per investment cost. It is due to the fact that less investment cost is needed for the wind turbine to generate the same amount of electricity as that from PV panel.
- From the energy point of view, both year-round reduction of primary energy usage and embodied energy decreases with the decrease of thickness for each type of insulation material. As a result, the external wall insulation board with a thickness of 2 cm and the sheep wool with a thickness of 7.5 cm are found to have the smallest payback year of embodied energy and the largest net life cycle energy consumption reduction per embodied energy. Moreover, although year-round energy consumption reduction of the triple-glazed window is smaller than that of PV panel and wind turbine, the triple-glazed window has better life cycle performance, namely, smaller payback year

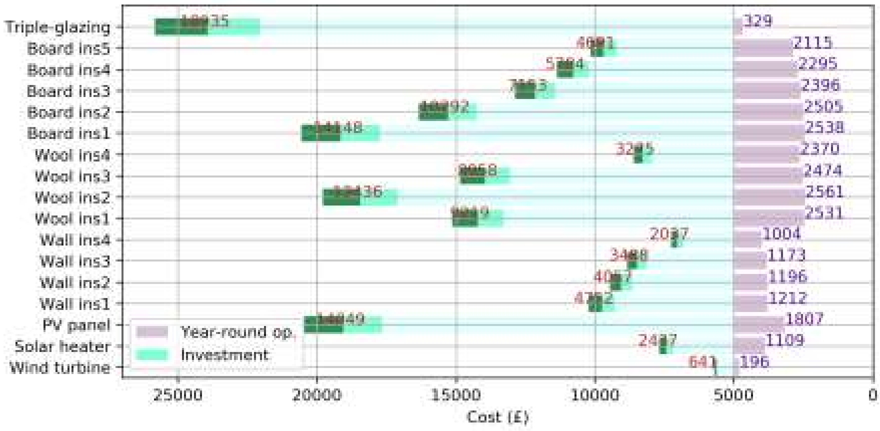
of embodied energy and larger net life cycle energy consumption reduction per embodied energy. It is because less embodied energy is needed for the triple-glazed window to provide the same amount of energy usage as that from PV panel and wind turbine.

- From the environmental point of view, both year-round reduction of greenhouse gas emissions and embodied carbon decreases with the decrease of insulation thickness for each type of insulation material. As a result, the external wall insulation board with a thickness of 2 cm and the sheep wool with a thickness of 7.5 cm are found to have the smallest payback year of embodied carbon and largest net life cycle greenhouse gas emissions reduction per embodied carbon.

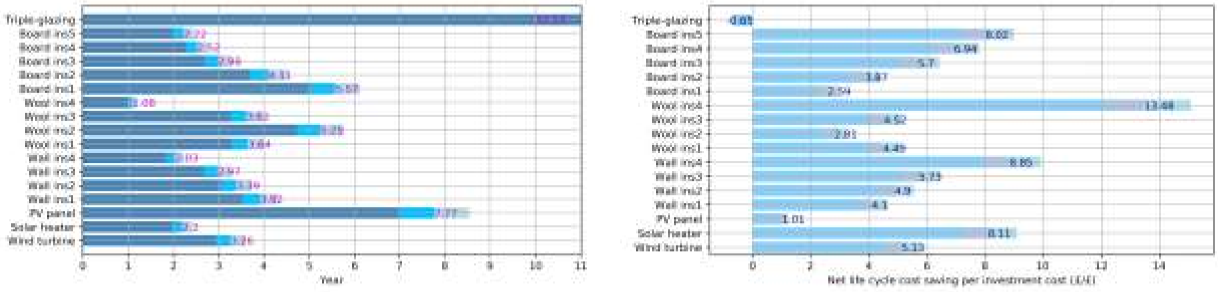
It indicates that retrofitting optimisation should be conducted in view of the entire life cycle performance. Moreover, although there exists a variety of embodied carbon, investment cost and embodied energy of each material, the overall trends of life cycle performance (i.e. payback year of embodied carbon, investment cost and embodied energy, as well as life cycle performance) among different retrofitting options do not change.

It is also seen that the optimal retrofitting option would be different when retrofitting objectives are different.

- From the economic point of view, the 7.5 cm sheep wool would result in the smallest payback year of investment cost and largest net life cycle cost saving per investment cost, followed by the 2 cm external wall insulation board, solar heater, wind turbine and PV panel. The payback year of the triple-glazed window is 57.53, mainly due to its high investment cost.
- From the energy point of view, the external wall insulation board with a thickness of 20 mm has the smallest payback year of embodied energy and the largest net life cycle energy reduction per embodied energy, followed by sheep wool with a thickness of 75 mm for roof insulation, solar heater, triple-glazed window, PV panel and wind turbine.
- From the environmental point of view, the external wall insulation board with a thickness of 20 mm also has the smallest payback year of embodied carbon and the largest net life cycle carbon reduction per embodied carbon, followed by sheep wool with a thickness of 75 mm for roof insulation, solar heater, triple-glazed window, PV panel and wind turbine.

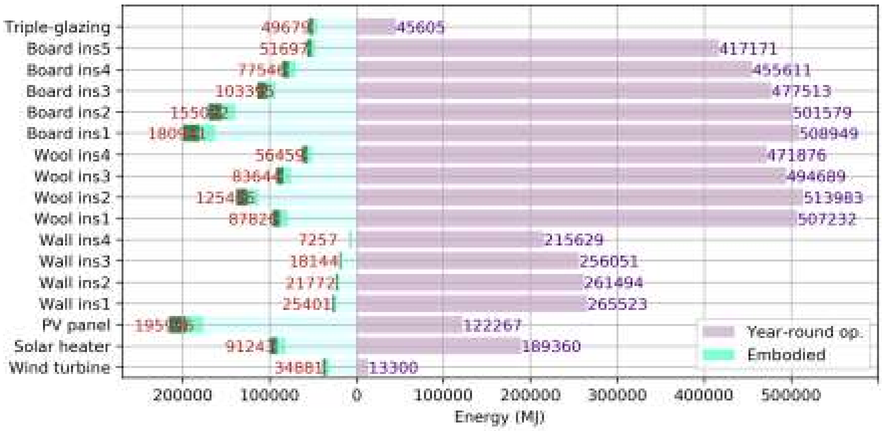


Investment cost and year-round operating cost-saving

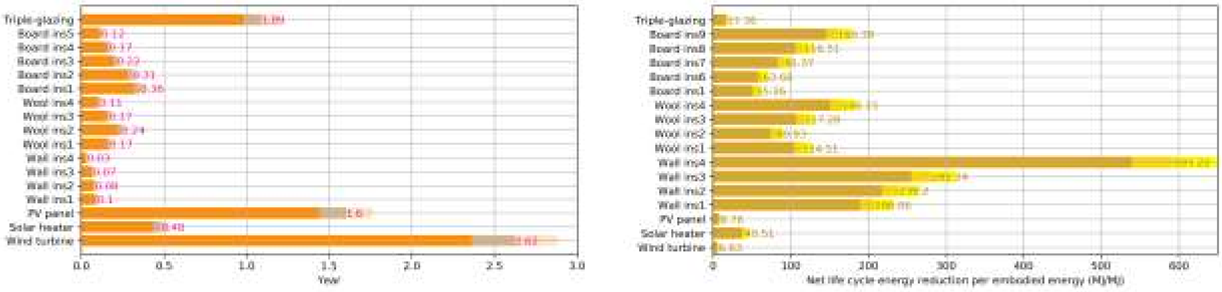


Payback year of investment cost Net life cycle cost saving per investment cost

Fig. 17. Life cycle economic performance of different retrofitting materials.

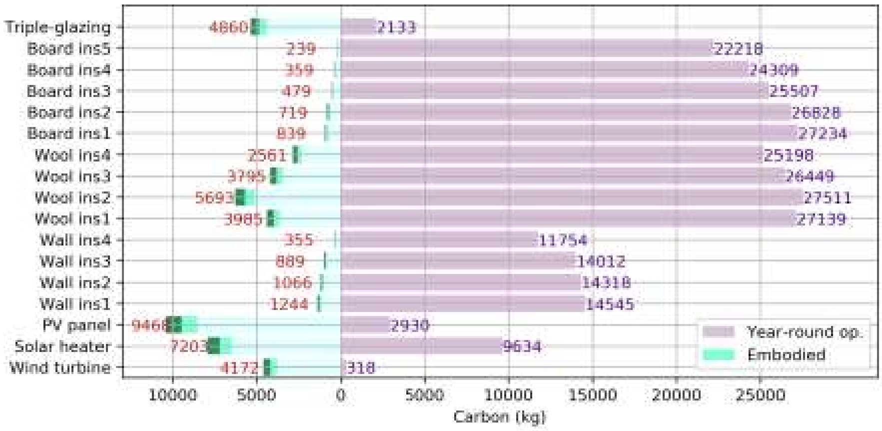


Embodied energy and year-round operating energy reduction

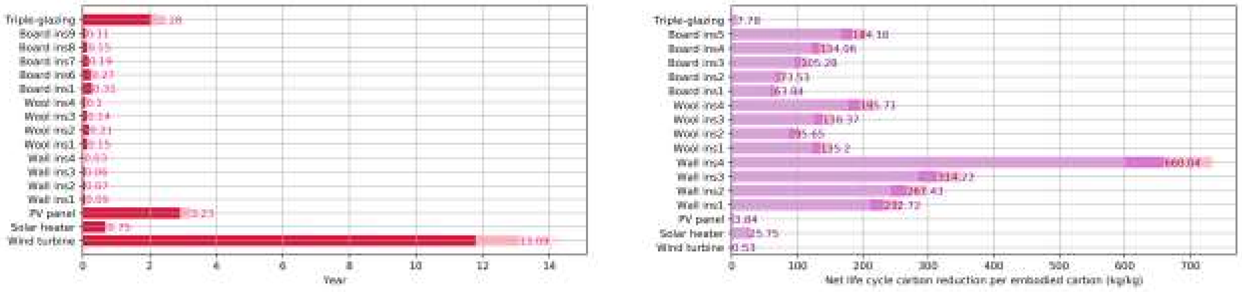


Payback year of embodied energy Net life cycle energy reduction per embodied energy

Fig. 18. Life cycle energy performance of each retrofitting material.



Embodied carbon and year-round operating carbon reduction



Payback year of embodied carbon Net life cycle carbon reduction per embodied carbon

Fig. 19. Life cycle environmental performance of each retrofitting material.

5.3 Retrofitting optimisation results

The retrofitting optimisation is conducted to select the optimal retrofitting solutions under different objectives (e.g. net reduction of life cycle cost from unit investment cost, net reduction of life cycle energy usage from unit embodied energy, and net reduction of life cycle carbon emissions from unit embodied carbon) at different embodied carbon, investment cost and embodied energy. The payback year of embodied carbon, investment cost and embodied energy of each retrofitting solution is evaluated. The cost-saving, primary energy usage reduction and greenhouse gas emissions reduction performance during its life cycle is also investigated under different situations. The annual salvage value rate and recycle ratio is kept at 5% and 40%, respectively, while the life span for all the retrofitting materials is assumed to be 20 years.

5.3.1 Retrofitting towards optimal life cycle cost saving

The optimisation results of retrofitting towards optimal life cycle economy performance are summarised in Fig. 20, along with its actual embodied carbon and energy, as well as its payback year and life cycle payback performance.

- The sheep wool with a thickness of 75 mm and density of 18 kg/m^3 is the first option in retrofitting, followed by the external wall insulation board with a thickness of 20 mm, solar heater and wind turbine.
- According to Fig. 17, the net life cycle cost saving per investment cost of the solar heater (8.11 MJ/MJ) is higher than that of PV panel (1.57 MJ/MJ). Thus, the solar heater has the priority over PV panel if the optimisation objective is life cycle economy performance.
- The embodied carbon and energy increases with the growth in investment cost. The maximum possible investment cost is £42,497, at which the embodied energy is 1.47×10^6 MJ while the embodied carbon is 1.17×10^5 kg, respectively. When sheep wool and external wall insulation board are chosen as retrofitting options, the increasing rate is relatively low due to the smaller embodied energy and carbon of unit sheep wool and external wall insulation board. On the contrary, when the retrofitting options include the solar heater and wind turbine, the increasing rate of embodied energy and carbon becomes quite large.
- The payback year of investment cost is constant when roof insulation is implemented. It gradually increases with the increase in investment cost because retrofitting options with the lowest payback year would be chosen first. The payback year of investment cost is 2.10 when the investment cost is £50,500.
- The payback year of embodied energy and carbon is constant when roof insulation is implemented. There is a slight decrease with the implementation of wall insulation because the payback year of embodied energy and carbon of insulation board is lower than that of the sheep wool. After that, the payback year of embodied carbon and energy increases with the growth in investment cost because solar heater and wind turbine has a larger payback year of embodied energy and carbon. The payback year of embodied energy and carbon is 0.41 and 0.63 when investment cost is £42,497.
- Life cycle reduction of carbon emissions, economic costs and primary energy usage continually increase with the growth in investment cost. It suggests that the more materials being retrofitted, the more economical, energetic and environmental benefits can be gained. The largest life cycle reduction of carbon emissions, economic costs and primary energy usage is 3.5×10^6 kg, £3.6×10^5 and 6.9×10^7 MJ and, respectively.

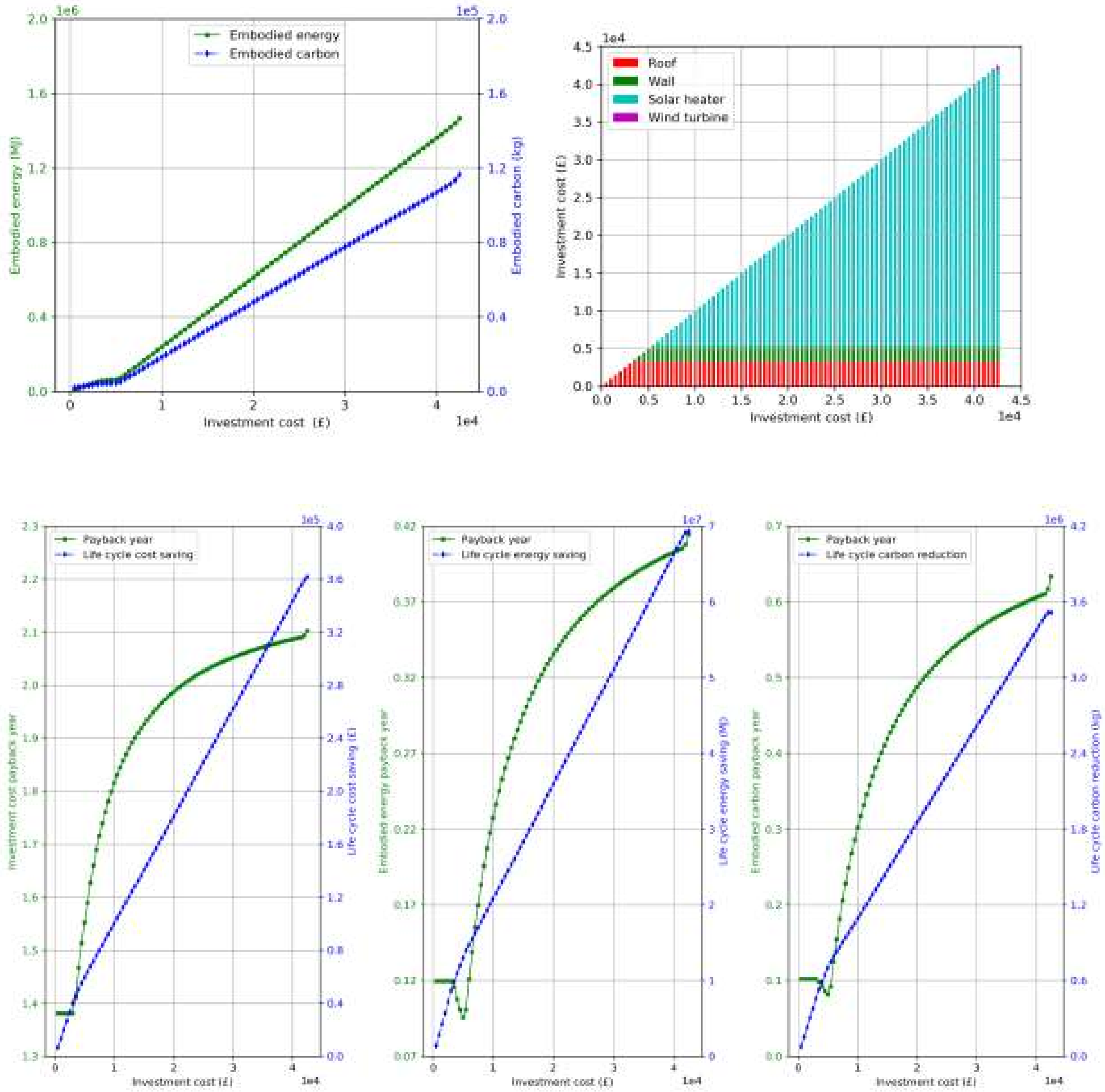


Fig. 20. Optimisation performance towards life cycle cost saving.

5.3.2 Retrofitting towards optimal life cycle energy consumption

The optimisation results of retrofitting towards optimal life cycle energy performance are summarised in Fig. 21, along with its actual investment cost and embodied carbon, as well as its payback year and life cycle payback performance.

- The external wall insulation board with a thickness of 20 mm is the first option in retrofitting, followed by sheep wool with a thickness of 75 mm and density of 20 kg/m^3, solar heater, triple-glazed windows and wind turbine.

- According to Fig. 18, net life cycle energy reduction per embodied energy of solar heater (40.51 MJ/MJ) is larger than that of PV panel (11.48 MJ/MJ). Thus, the solar heater has the priority over PV panel if the optimisation objective is life cycle energy performance.
- The investment cost and embodied carbon also increase with the increase in embodied energy. The increasing rate of investment cost is extremely high when the triple-glazed window is selected as one of the retrofitting options. The maximum possible embodied energy is 1.9×10^6 MJ, at which the investment cost is £2.3×10^5 while the embodied carbon is 1.6×10^5 kg, respectively. When sheep wool and external wall insulation board are chosen as retrofitting options, the increasing rate of investment cost is relatively low due to the smaller investment cost of unit sheep wool and external wall insulation board. On the contrary, when the retrofitting options include a triple-glazed window, the increasing rate of investment cost is quite high.
- The payback year of embodied energy gradually increases with the increase of embodied energy because retrofitting options with the lowest payback year would be firstly selected. The payback year of embodied energy is 0.49 when the embodied energy is 1.9×10^6 MJ.
- There exists a slight decrease in payback year of investment cost with the implementation of roof insulation. The payback year of investment cost and embodied carbon then increases with the increase in embodied energy owing to the fact that solar heater and triple-glazed window has a larger payback year of investment cost and embodied carbon. There also exists a slight decrease in the payback year of investment cost with the implementation of the wind turbine. The largest payback year of investment cost and embodied carbon is 10.0 and 0.8, respectively.
- The reduction of carbon emissions and energy usage during its life cycle continually increases with the rise of embodied energy. It suggests that the more materials being used in retrofitting, the more energetic and environmental profits can be obtained. The most considerable reduction of carbon emissions and energy usage during its life cycle is 3.9×10^6 kg and 7.8×10^7 MJ, respectively.
- When roof insulation, wall insulation and the solar heater is adopted, the cost saving of the whole life cycle increases with the increase of embodied energy. However, there exists a decrease in life cycle cost savings owing to triple-glazed window's high investment cost. The highest life cycle cost saving can be achieved is £3.6×10^5.

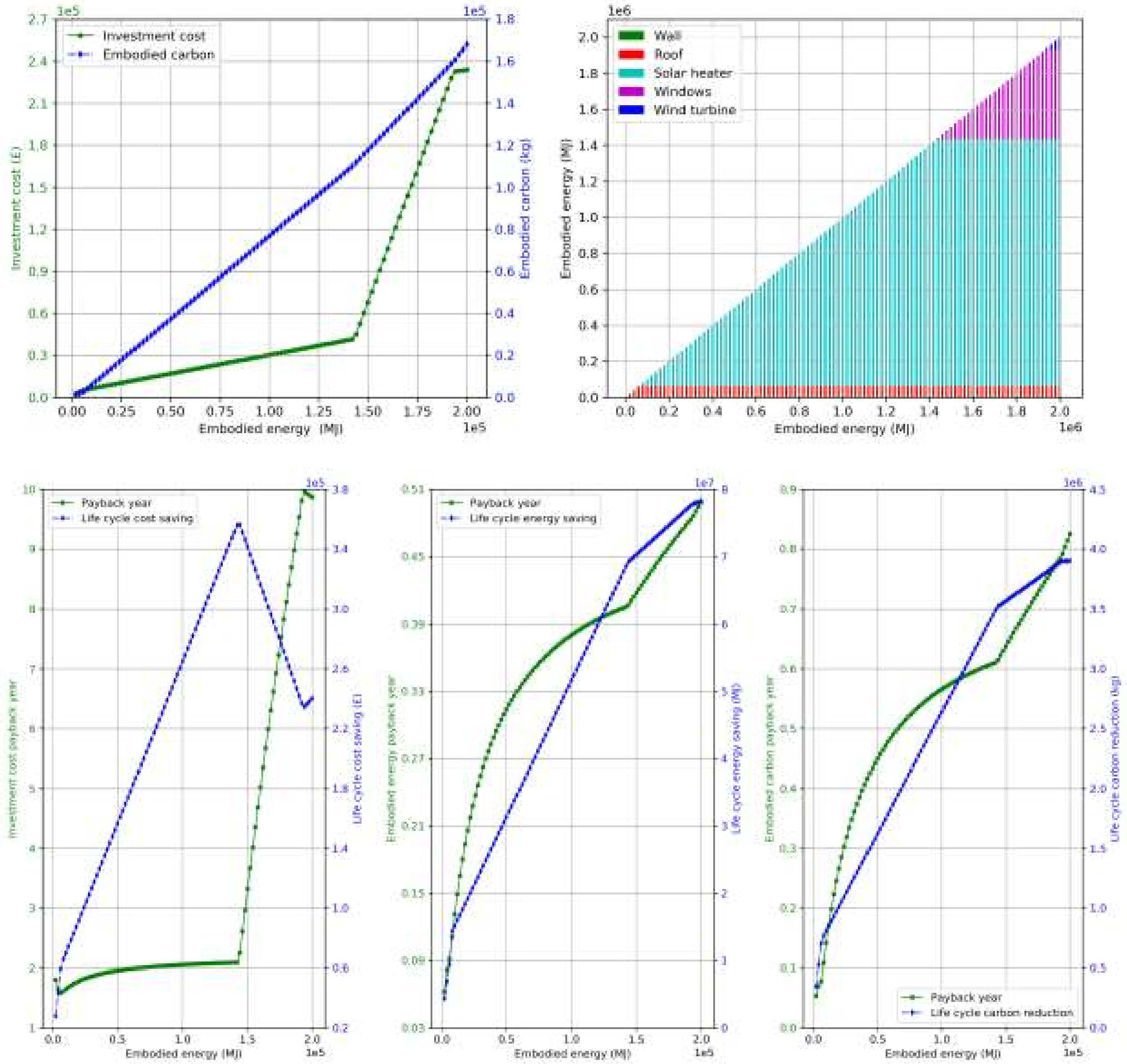


Fig. 21. Optimisation performance towards life cycle energy reduction.

5.3.3 Retrofitting towards optimal life cycle greenhouse gas emissions

The optimisation results of retrofitting towards optimal life cycle carbon performance are summarised in Fig. 22, along with its actual investment cost and embodied energy, as well as its payback year and life cycle payback performance.

- The external wall insulation board with a thickness of 20 mm is the first option in retrofitting, followed by sheep wool with a thickness of 75 mm and density of 20 kg/m^3, solar heater, wind turbine and triple-glazed window.
- According to Fig. 19, the net life cycle carbon reduction per embodied carbon of solar heater (25.75 kg/kg) is larger than that of PV panel (5.19 kg/kg). Thus, the solar heater has the priority over PV panel if the optimisation objective is life cycle environmental performance.

- The investment cost and embodied energy also increase with the rise in embodied carbon. The relatively high increasing rate of investment cost is found when the triple-glazed window is adopted, while the increasing rate of embodied energy is relatively constant. When the embodied carbon is 1.64×10^5 kg, the investment cost is £2.3×10^5 while the embodied energy is 2.0×10^6 MJ, respectively.
- The payback year of embodied carbon gradually increases with the rise of embodied carbon because retrofitting options with the lowest payback year would be firstly selected. The payback year of embodied carbon is 0.81 when the embodied carbon is 1.64×10^5 kg.
- The payback year of investment cost and embodied energy increases with the increase in embodied carbon. The largest payback year of investment cost and embodied energy is 9.9 and 0.49, respectively.
- The reduction of energy consumption and greenhouse gas emissions during its life cycle continually increases with the rise of embodied carbon. It suggests that the more materials being retrofitted, the more energetic and environmental profits can be obtained. The most considerable reduction of carbon emissions and energy usage during its life cycle is 7.8×10^7 MJ and 3.9×10^6 kg, respectively.
- When roof insulation, wall insulation and solar heater is adopted, the cost-saving during its life cycle increases with the increase of embodied energy. However, there exists a decrease in life cycle cost savings owing to triple-glazed window’s high investment cost. The highest life cycle cost saving that can be achieved is £3.6×10^5.

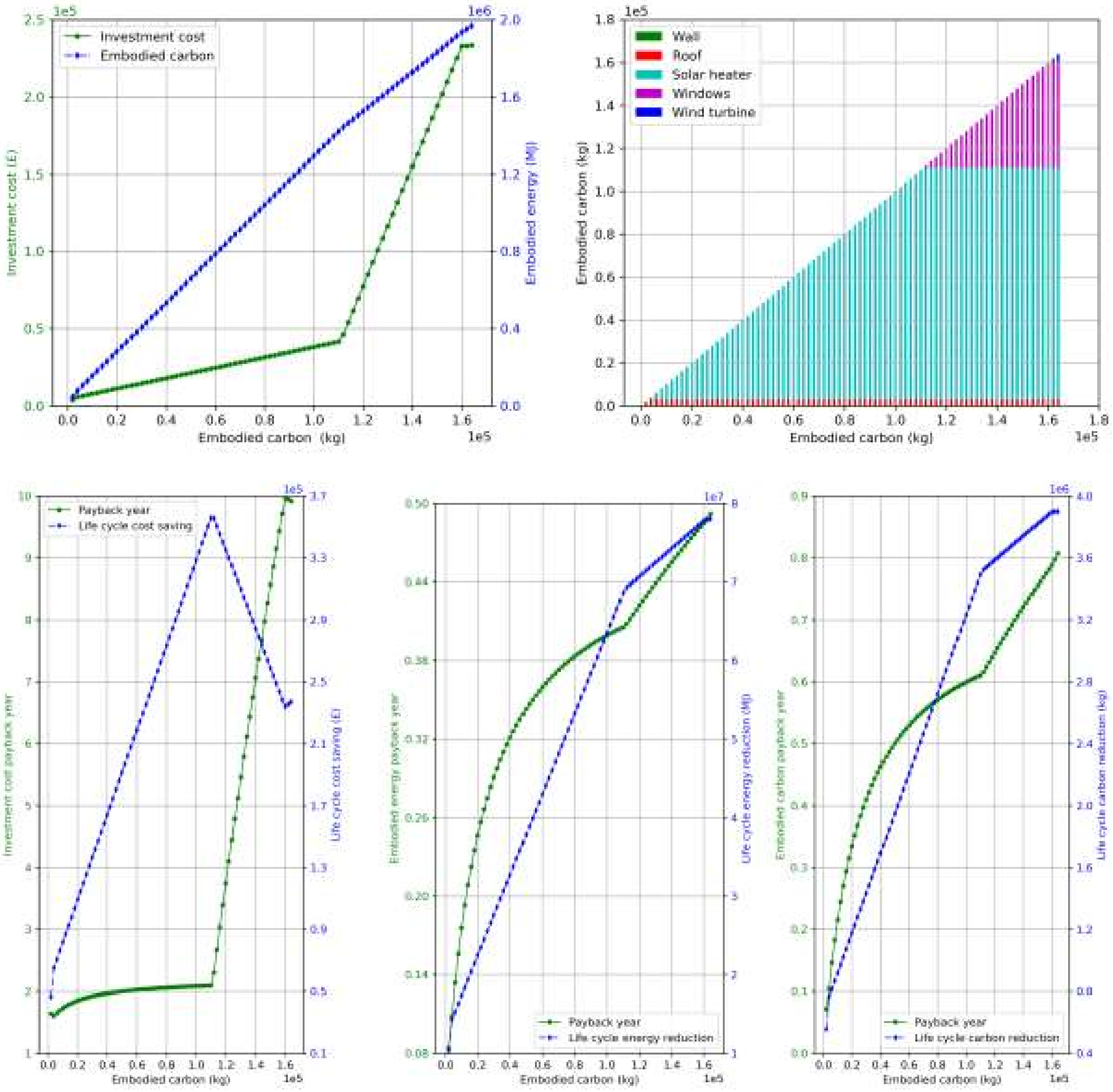


Fig. 22. Optimisation performance towards life cycle carbon reduction.

6 The implication of practical application and future study

A comprehensive assessment and optimisation on building retrofitting is conducted on an office building to improve its life cycle environment, economy and energy performance. The proposed life cycle assessment and optimisation approach is generalised and is able to be applied to different office buildings in different climates. The objective function is based on a fundamental definition (i.e. Equation. 10) of different life cycle characteristics such as net reduction of life cycle cost from unit investment cost, net reduction of life cycle energy usage from unit embodied energy, and net reduction of life cycle carbon emissions from unit embodied carbon. The value of these objective functions can be estimated using the collected information from different buildings. Moreover, the adopted retrofitting strategies, such as roof insulation, wall insulation, triple-glazed window, solar heater, PV panel and wind turbine, are quite common and popular in the market. Furthermore, the robust PSO algorithm is adopted to obtain the optimal retrofitting solutions.

To apply the proposed retrofitting optimisation approach in practical office buildings, the following procedures should be followed.

- The inputs to the retrofitting optimisation module should include historical energy usage profile, historical weather profile, building property information and inventory database. The historical energy consumption profile can also be estimated from energy bills if a building management system is not available. Historical weather data can also be obtained from weather reports websites [43-45] if a local weather station is not available. Building thermal properties can be estimated from the material of each component if a building information model is not available. This further proves the generalisation of the proposed approach by obtaining data from limited sources.
- After that, the optimal retrofitting solution would be obtained using the PSO algorithm and the generalised life cycle assessment criteria, life cycle optimisation module and corresponding mathematical models.
- The payback year of embodied carbon, investment cost, and embodied energy, along with life cycle economic costs, energy usage, and carbon emissions of the optimal retrofitting solution, can also be estimated using the generalised life cycle assessment criteria.

In this study, wall insulation, roof insulation, triple-glazed window, PV panel, solar collector and wind turbine are chosen as the potential retrofitting options. In the future study, the life cycle environment, economy and energy performance of ground source heat pump, biomass boiler, heat storage and electricity storage can also be investigated. In the current study, the assessment and optimisation approach is implemented on an office building. The retrofitting performance of the residential buildings also worth evaluating to help achieve zero-carbon ambition.

7. **Conclusion**

Although some life cycle energy and carbon assessment approaches were adopted in previous studies, it is generally based on performance evaluation of single adoption of retrofitting option. There is no research work optimising the energy usage and carbon emissions of combined retrofitting measures during its life cycle. This significant research gap drives the research question: How to select retrofitting measures to achieve overall low greenhouse gas emissions, economic costs and energy usage of the retrofitted building during its life cycle. Therefore, the objective and distinguish innovation of this research is to propose a comprehensive life cycle assessment and optimisation approach for building retrofitting. In view of life cycle optimal performance, the trade-off between investment cost and year-round operating cost-saving; embodied energy and year-round operating primary energy usage reduction; as well as embodied carbon and year-round operating greenhouse gas emissions reduction of different retrofitting options are investigated. The optimisation is conducted from the life cycle environment, economy and energy points of view to determine the optimal combination of different retrofitting options. This study focuses on the passive retrofitting options, including envelope up-gradation (e.g. wall insulation, roof insulation and triple-glazed window) and renewable energy devices (e.g. PV panel, wind turbine and solar heater). An office building is adopted in the case study to explore the life cycle performance of the proposed retrofitting assessment and optimisation approach.

Firstly, the effects of the annual salvage value ratio on investment cost payback year and life cycle cost saving on different retrofitting materials are investigated.

- A larger annual salvage value rate indicates a higher investment cost degradation rate of the retrofitting materials. Thus, the payback year of investment cost increases while life cycle cost saving drops with the increase of the annual salvage value rate.
- On the contrary, the larger recycle ratio indicates more embodied carbon and energy of the materials can be reutilised at the end-of-life stage. Therefore, the payback year of embodied energy and carbon decreases with the rise of recycle ratio, while the reduction of life cycle carbon emissions and energy usage rises with the increase of material recycle ratio.

Next, the trade-off between investment cost and operating year-round cost-saving; embodied energy and year-round operating energy consumption reduction; as well as embodied carbon and year-round greenhouse gas emissions reduction, is investigated.

- Although the year-round cost saving of wind turbine is smaller than that of PV panel, the wind turbine has better life cycle economy performance in terms of shorter payback year of investment cost and higher life cycle cost saving per investment cost.
- Although year-round energy consumption reduction of the triple-glazed window is smaller than that of PV panel and wind turbine, the triple-glazed window has better life cycle energy performance in terms of smaller payback year of embodied energy and higher life cycle energy consumption reduction per embodied energy.
- Although insulation material with a smaller thickness has a smaller year-round reduction of carbon emissions, economic costs, and energy usage, it has better life cycle performance in terms of payback year and life cycle reduction of carbon emissions, economic costs and energy usage.
- Apart from the high-cost triple-glazed window, the investment cost payback year and net life cycle cost saving per investment cost of different retrofitting materials is within the range of 1.08-7.77 years and 1.57-13.48 £/£. The embodied energy and carbon payback year is within the range of 0.03-2.62 years and 0.03-13.09 years, respectively. The net reduction of life cycle energy usage

from unit embodied energy and net reduction of life cycle carbon emissions from unit embodied carbon are within the range of 6.63-593.22 MJ/MJ and 0.53-660.04 kg/kg, respectively.

- The variation of payback year of investment cost and life cycle economic cost saving due to the change of investment cost increases with the increase of annual salvage ratio. Meanwhile, owing to the change of embodied carbon and energy, variation of payback year of embodied energy and carbon, as well as life cycle carbon emissions and energy usage, decreases with the increase of material recycle ratio.

Lastly, the retrofitting optimisation is conducted at three objectives respectively at different embodied carbon, investment cost and embodied energy.

- To achieve the maximum cost saving capability during the life cycle, the sheep wool with a thickness of 75 mm for roof insulation would be the primary retrofitting option, followed by the insulation board with a thickness of 20 mm for wall insulation and solar heater for spacing heating.
- To achieve the maximum primary energy usage reduction during the life cycle, the retrofitting options would be chosen in the order of the insulation board with the thickness of 20 mm for wall insulation, the sheep wool with the thickness of 75 mm for roof insulation, solar heater for space heating, triple-glazed window and wind turbine for electricity production.
- To achieve the maximum greenhouse gas emissions reduction during the life cycle, the retrofitting options would be chosen in the order of the insulation board with the thickness of 20 mm for wall insulation, the sheep wool with the thickness of 75 mm for roof insulation, solar heater for space heating, wind turbine for electricity production and triple-glazed window.
- The largest achievable reduction of greenhouse gas emissions, economic costs and primary energy usage during the whole life cycle are 2.8×10^6 kg, £2.7×10^5 and 4.8×10^7 MJ, respectively.
- The payback year of triple-glazed window and wind turbine is longer than its life span. However, it shows great potential in energy and carbon reduction due to its short payback year of embodied energy and carbon.

Although the above conclusion values are based on the case study, the proposed retrofitting assessment and optimisation approach can be adopted in different office buildings in different climates, as discussed in Section 6.

In conclusion, the proposed retrofitting optimisation approach can help building retrofitting experts gain insight into the trade-off between embodied carbon and energy against the year-round reduction of carbon emissions and primary energy usage. Thus the building can be achieve its optimal life cycle performance. The research outcome can provide the government with approach-based net-zero retrofitting guidance and building engineers with sustainable retrofitting solutions.

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Nomenclature

a	Unit cost, energy and carbon at production stage
A	Performance at production stage (i.e. cost, energy and carbon)
b	Unit cost, energy and carbon at use stage
B	Performance at use stage (i.e. cost, energy and carbon)
c	Unit cost, energy and carbon at end-of-life stage
C	Performance at end-of-life stage (i.e. cost, energy and carbon)
D	Performance beyond the system boundary (i.e. cost, energy and carbon)
G	Global solar radiation
LC	Life cycle performance (i.e. cost, energy and carbon)
ls	Life span
N	Number of retrofitting options
NLC	Net life cycle saving/reduction
Q	Energy demand
r	Ratio
S	Surface area
T	Temperature
x	Design area/power
y	Type
Y	Payback year
η	Efficiency
ε	Correction coefficient

Subscripts

AC	Air conditioning system
B	Gas boiler
c	Cooling
db	Dry-bulb
e	Office equipment
ele	Electricity
h	Heating
i	Performance (i.e. cost, energy or carbon)
ia	Indoor air
inf	Infiltration
j	Retrofitting options
l	Lighting
o	Occupancy
oa	Outdoor air
$post$	Post-retrofitting
pre	Pre-retrofitting
rec	Material recycle
ref	Reference
sal	Salvage
$solar$	Solar heat
$trans$	Transmission

vent	Ventilation

Abbreviations

COP	Coefficient of performance
IDA-ICE	IDA Indoor Climate and Energy
PSO	Particle swarm optimisation
PV	Photovoltaic

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