A data-driven life-cycle optimisation approach for building retrofitting: A comprehensive assessment on economy, energy and environment

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Abstract:

A novel data-driven life-cycle optimisation approach is proposed for building retrofitting. The innovation points include big-data information, integrated retrofitting design, and life-cycle optimisation through a comprehensive assessment of the economy, energy and environment. The optimal retrofitting plan is selected to maximise its life-time cost-saving, energy reduction and carbon reduction. The proposed retrofitting optimisation approach is tested on a real-world building. The standard retrofitting options include roof insulation, wall insulation, wind turbine, solar heater, biomass boiler, combined heat and power system and photovoltaic panel. The historical energy consumption, building information, historical weather data, and inventory data is adopted in the data-driven model to replicate the real-world case. Although building retrofitting would increase economic, energy and environmental effects at the beginning of its life-cycle due to increased investment cost, embodied energy and carbon of retrofitting materials, the overall life-cycle cost, energy and carbon would be lower than those non-retrofitted buildings. It is found that envelope insulation has the lowest unit return cost, energy and carbon, followed by the solar heater, combined heat and power system, biomass boiler, wind turbine and photovoltaic panel. Through the optimal retrofitting plan, 39% life-time cost-saving, 55% life-time energy reduction and 59% life-time carbon reduction can be achieved at an investment cost of £1.32 × 10^6.

Keywords:
Building retrofitting; Life cycle optimisation; Embodied energy; Embodied carbon; Data-driven; Real-world case.

1. Introduction

The latest investigation points out that building construction and operation occupies the most significant energy consumption and carbon emissions globally in 2018 [1]. Energy-efficient buildings play an essential role in energy resources preservation and climate change mitigation. Even though recently constructed buildings are more energy-efficient, the fact is that 80% of buildings in 2050 have already been constructed [2]. As a result, attention should be turned to decarbonise existing buildings through effective retrofitting measures. It is critical to choose building retrofitting materials with small life-cycle energy consumption and carbon footprint.

1.1 Literature review

Most of the existing research works focus on minimising energy consumption during the building operating stage. Asadi *et al.* [3] proposed a multi-objective optimisation model for a multi-family house. The optimisation purpose is to select appropriate retrofitting materials to reduce energy consumption over a fixed period in a cost-effective manner. The decision variables include the type of windows, wall insulation, roof insulation and solar heater. Fan *et al.* [4] suggested a multi-objective optimisation for an apartment building. The optimisation objective was to make the best use of financial investment to maximise energy savings and economic benefits over a fixed period. The decision variables included the type of windows, wall insulation, roof insulation and solar heater. Wang *et al.* [5] presented a differential evolution algorithm-driven multi-objective optimisation model. The optimisation objective was to determine the optimal retrofitting solutions to minimise the overall costs within a particular time frame. Twelve types of energy-efficient retrofitting facilities were considered and optimised in the building, including lighting facilities, heat pumps, chillers, control systems and other devices. Chang *et al*. [6] developed a multi-objective optimisation model for two apartments and two wooden houses. The energy consumption, thermal discomfort, environmental effects, and economic impacts were deliberated as a synthesised objective function over a certain period. Rosso *et al.* [7] proposed a genetic algorithm-driven multi-objective optimisation model for envelope retrofitting. The retrofitting options included a glazing system, opaque envelope insulation system, solar shading, sunspace, solar heater, and photovoltaic (PV) panel. The optimisation objects contained investment cost, year-round energy demand and cost, as well as carbon emission reduction. Alkhateeb *et al.* [8] examined the potential of adopting PV panels to transform an office building into a net-zero building. The primary purpose was to satisfy the building electrical energy demand through PV panels.

Although building energy performance can be improved through these retrofit measures, extra materials and elements are applied. It would lead to more significant embodied energy and carbon impacts. Hence, it is crucial to evaluate the additional environmental effects of retrofitting measures alongside the post-retrofitting building energy consumption. Ambrose *et al.* [9] examined the life-cycle primary energy implication of retrofitting a wood-framed apartment building through efficient hot water taps, improved thermal insulation of the envelope, and heat recovery from ventilation air. Chiara *et al.* [10] evaluated the life-cycle primary energy effects of material alternatives for building retrofitting, including thermal insulation, external building cladding and windows. Marta *et al.* [11] developed an approach for identifying environmental and cost-effective retrofitting procedures. The investigated retrofitting options included envelope insulation, heat pump, lamp, and lift replacement. The life-cycle energy, economic and environmental impacts of each retrofitting option were explored. Georgios *et al.* [12] utilised a life-cycle assessment approach to compare the environmental impact of using solar conversion systems (i.e. PV panel and solar heater) to cover the energy requirement of a typical Greek detached house. The assessment criteria include human health, ecosystem quality and energy resources. Tang *et al.* [13] proposed a multiple-criteria optimisation approach for transforming residential buildings towards net-zero energy buildings. The retrofitting options included envelope insulation, window substitution, boiler replacement and mechanical ventilation.

Although life-cycle energy and carbon of different retrofitting measures was evaluated in previous works, there was a lack of approach to determine the optimal renovation plan based upon the comprehensive life-cycle economy, energy and environment criteria. Moreover, the main focus of existing retrofitting measures was life-cycle cost. Rabani *et al.* [14] developed an optimisation model to determine the optimal refurbishment solutions with the minimum life-cycle cost. The retrofitting solutions mainly include roof insulation, wall insulation, as well as temperature control of air handling units. Shen *et al.* [15] developed a fast multi-objective optimisation approach and decision-making support for building retrofitting design to curtail life-cycle cost. The retrofitting options include building wall insulation, roof insulation, natural ventilation, air infiltration level, heating and cooling system efficiency, and renewable energy systems. The optimisation objectives include operating energy reduction, retrofitting investment and thermal comfort. Jafari *et al.* [16] developed an optimisation outline to select the optimal refurbishment scheme to make the most of economic benefits during the life-cycle of the building. The retrofitting options included energy equipment replacement, envelope insulation, and solar collector installation.

Table 1. Summary of literature review.

Ref.	Building type	Retrofitting options				Data information				Optimisation objective				Published Year
		Envelope insulation	Solar energy	Wind energy	Biomass energy	Historical weather data	Historical energy data	Inventory data	Building property	Energy over a fixed period	Life-cycle cost	Life-cycle energy	Life-cycle carbon	
[9]	Apartment building	Y	N	N	N	N	N	N	Y	N	N	E	N	2010
[3]	Multi-family house	Y	Y	N	N	N	N	N	Y	Y	N	N	N	2012
[5]	No specific building	N	N	N	N	N	N	Y	N	Y	N	N	N	2014
[4]	Apartment	Y	Y	N	N	N	N	N	Y	Y	N	N	N	2016
[16]	House	Y	Y	N	N	N	S	Y	Y	N	O	N	N	2017
[12]	Residential building	N	Y	N	N	Y	R	N	N	N	N	N	E	2018
[8]	A federal building	Y	Y	N	N	Y	S	N	N	N	N	E	N	2019
[15]	Campus building	Y	Y	N	N	Y	R	N	Y	N	O	N	N	2019
[6]	Apartments and houses	Y	Y	N	Y	N	N	N	Y	Y	N	N	N	2020
[7]	Residential buildings	Y	Y	N	N	N	S	N	Y	Y	N	N	N	2020
[10]	Multi-family house	Y	N	N	N	N	N	Y	Y	N	E	E	N	2020
[11]	Office building	Y	N	N	N	N	N	Y	N	N	N	E	E	2020
[13]	Residential buildings	Y	N	N	N	N	N	Y	Y	N	N	E	N	2020
[14]	Generic office building	Y	N	N	N	N	N	N	N	N	O	N	N	2020
Previous works	Residential and office buildings	Limited retrofitting measures and individual effect assessment.				Degree day or software-based simulation				Mainly optimise yearly energy consumption or life-cycle cost				Research gaps
This study	Real-life office building	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Innovation
		Integrated retrofitting design				Big-data information				Life-cycle optimisation				
		An optimised set of retrofitting measures to enhance retrofitting performance				Accurate real-life building performance evaluation through modelling using big-data information				Life-cycle energy and carbon minimisation through the new approach with the optimisation objective of life-time energy and carbon				Contribution

E: Evaluation
Y: Yes
N: No
O: Optimisation

1.2 Research gaps

The building type, retrofitting options, available data information, optimisation objective and published year of the literature as mentioned earlier are summarised in Table 1. Although various retrofitting measures have been evaluated while several optimisation approaches were proposed, the research gaps are identified as follows:

- Although most research works adopted the actual residential building in the case study, degree day or simulation software was generally adopted to estimate the building energy performance. However, the degree-day may not be sufficient to investigate the actual operating performance of the building, while the thermodynamic models-based simulation software may not indicate the real-life situation. Therefore, the first research gap is inaccurate building performance evaluation results from the degree day or software-based simulation.
- Envelope up-gradation (i.e. roof insulation, wall insulation and triple-glazing window) and solar conversion system (i.e. solar heater and PV panel) were commonly adopted in most previous research works. The individual performance of each retrofitting measure is evaluated. However, simultaneous adoption of several retrofitting measures, along with other options such as biomass-fuelled CHP system, biomass boiler, and wind turbine, may result in enhanced energy performance. Therefore, the second research gap lies in the downgraded retrofitting performance owing to limited retrofitting measures and individual effect assessment.
- The objective of retrofitting optimisation generally focused on the year-round operating energy or life-cycle cost. However, some retrofitting materials contain higher embodied energy and carbon. Its life-cycle energy and carbon might be large even though the year-round operating energy and the life-cycle cost is relatively small. Therefore, the third research gap is non-optimal life-cycle energy and carbon performance as the optimisation objective was yearly operating energy consumption or life-cycle cost.

1.3 Innovation and contribution

To overcome the shortcomings of existing literatures, a novel data-driven life-cycle optimisation approach is proposed for building retrofitting. To make better comparison, the innovation and contribution of the proposed approach are also summarised in Table 1. As demonstrated in Fig. 1, the proposed retrofitting optimisation approach involves three levels of innovation, including big-data information, integrated retrofitting design and life-cycle optimisation:

- Big-data information: The big-data information includes historical energy consumption profile from the building energy management system; actual building thermal property information from the building information modelling system; historical weather data from the local weather station; and the real-world life-cycle inventory data from various latest sources. These different data types are pre-processed and co-ordinately serve as the database for driving the life-cycle optimisation approach. This database can also demonstrate the building retrofitting impacts in a real-world situation. This innovation tackles the first research gap, as it provides accurate real-life building performance evaluation through modelling using big-data information.

- Integrated retrofitting design: The integrated retrofitting design considers a wide variety of retrofitting measures, such as wall insulation and roof insulation for decreasing thermal energy demand, solar heater and PV panel for utilising solar energy, as well as biomass-fuelled CHP system and biomass boiler for using biomass energy. The accumulative effects of retrofitting measures are investigated. The coordination of different retrofitting measures can achieve enhanced retrofitting performance in satisfying building heating and electrical energy demand. This innovation sorts out the second research gap, as it provides enhanced energy performance through a set of retrofitting measures.
- Life-cycle optimisation: The retrofitting optimisation is based on life-cycle performance of economy, energy and environment. The optimisation objectives include life-time cost-saving, life-time energy reduction and life-time carbon reduction. The embodied energy and carbon of raw material extraction and manufacturing, as well as the released energy and carbon during the end-of-life recycling stage, is considered. This innovation resolves the third research gap by developing an approach to select an optimal retrofitting plan towards life-cycle energy and carbon reduction maximisation.

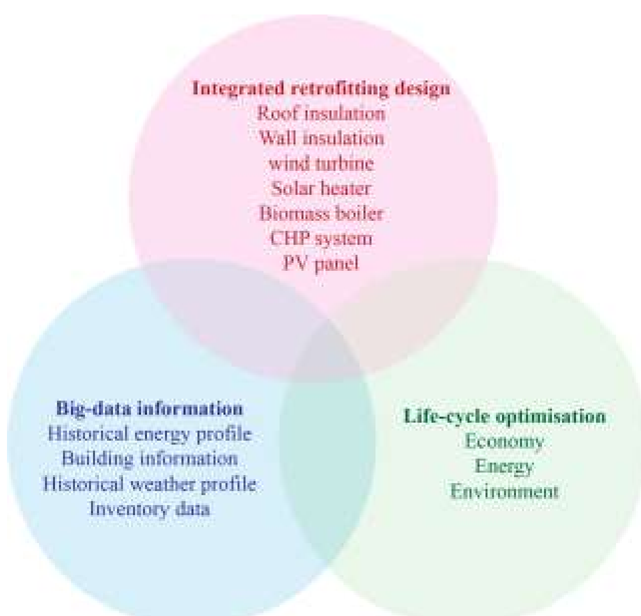


Fig. 1. Three-level of innovation.

2. Theory of data-driven life cycle retrofitting optimisation approach

The procedure of the proposed data-driven life-cycle optimisation approach is illustrated in Fig. 2. The core part of the optimisation approach is the life-cycle economy, energy and environment optimisation module. The big-data input of the proposed optimisation approach includes historical energy profile, building information, historical weather profile and real-world inventory data. The output is the optimised retrofitting plan, composed of the design area and design power of different retrofitting options.

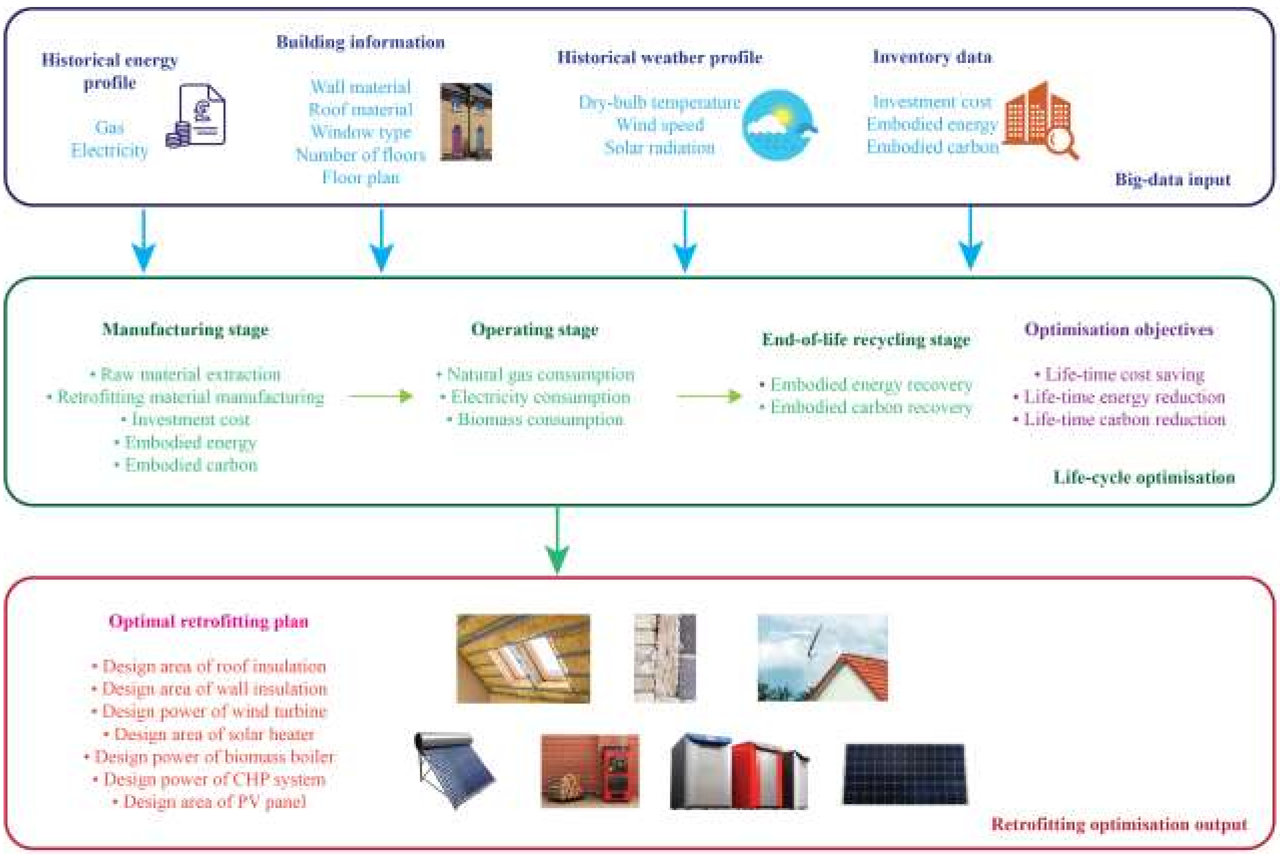


Fig. 2. Flowchart of the proposed data-driven life-cycle optimisation approach.

2.1 Decision variables

The decision variables of retrofitting optimisation include the surface area of roof insulation (X_{RI}), the surface area of wall insulation (X_{WI}), design power of wind turbine (X_{WT}), design area of solar heater (X_{SH}), design power of biomass boiler (X_{BB}), design power of CHP system (X_{CHP}) as well as design area of PV panel (X_{PV}).

2.2 Optimisation objective

There are three primary optimisation objectives in this study, including life-time cost saving ΔE_{CO}, life-time energy reduction ΔE_{EN} and life-time carbon reduction ΔE_{CE}:

$$\Delta E_{CO} = E_{CO}^{pre} - E_{CO}^{post} \tag{1}$$
$$\Delta E_{EN} = E_{EN}^{pre} - E_{EN}^{post} \tag{2}$$
$$\Delta E_{CE} = E_{CE}^{pre} - E_{CE}^{post} \tag{3}$$

Before retrofitting, the operating cost E_{CO}^{pre}, energy consumption E_{EN}^{pre} and carbon emission E_{CE}^{pre} is mainly caused by natural gas and electricity consumption:

$$E_{CO}^{pre} = (e_{CO,ng}Q_{ng}^{pre} + e_{CO,ele}Q_{ele}^{pre}) \cdot LS \tag{4}$$
$$E_{EN}^{pre} = (e_{EN,ng}Q_{ng}^{pre} + e_{EN,ele}Q_{ele}^{pre}) \cdot LS \tag{5}$$
$$E_{CE}^{pre} = (e_{CE,ng}Q_{ng}^{pre} + e_{CE,ele}Q_{ele}^{pre}) \cdot LS \tag{6}$$
$$Q_{ng}^{pre} = \frac{Q_h^{pre}}{\eta_{GB}}$$

where, $e_{CO,ng}$, $e_{EN,ng}$ and $e_{CE,ng}$ indicates the operating cost, energy consumption and carbon emission of the unit natural gas consumption; $e_{CO,ele}$, $e_{EN,ele}$ and $e_{CE,ele}$ indicates the operating cost, energy consumption and carbon emission of unit electricity consumption; LS is the life span of the building. Before retrofitting, natural gas is generally adopted to drive the gas boiler for satisfying building heating demand. Therefore, the consumption rate of natural gas Q_{ng}^{pre} depends on the actual heating demand Q_h^{pre} and efficiency of the gas boiler η_{GB}.

The ability to quantify the economic cost, energy consumption and carbon emissions across the whole life-cycle using life cycle assessment has enabled the industry's understanding of the importance of embodied energy and carbon [17]. International standards [18] have been developed to ensure consistency and comparability of life cycle assessment outcomes. There are mainly three life-cycle stages for the building retrofitting materials [19], namely, manufacturing stage, operating stage and end-of-life recycling stage. After retrofitting, the overall life-cycle cost E_{CO}^{post} includes investment cost E_{CO}^{inv} and operating cost. The overall life-cycle energy E_{EN}^{post} includes embodied energy E_{EN}^{emb}, operating energy consumption and end-of-life recycle energy E_{EN}^{rec}. The overall life-cycle carbon includes embodied carbon E_{CE}^{emb}, operating carbon emission and end-of-life recyclable carbon E_{CE}^{rec}.

$$E_{CO}^{post} = E_{CO}^{inv} + \left(e_{CO,ng}Q_{ng}^{post} + e_{CO,ele}Q_{ele}^{post} + e_{CO,bio}Q_{bio}^{post}\right) \cdot LS \tag{7}$$
$$E_{EN}^{post} = E_{EN}^{emb} + \left(e_{EN,ng}Q_{ng}^{post} + e_{EN,ele}Q_{ele}^{post} + e_{EN,bio}Q_{bio}^{post}\right) \cdot LS - E_{EN}^{rec} \tag{8}$$
$$E_{CE}^{post} = E_{CE}^{emb} + \left(e_{CE,ng}Q_{ng}^{post} + e_{CE,ele}Q_{ele}^{post} + e_{CE,bio}Q_{bio}^{post}\right) \cdot LS - E_{CE}^{rec} \tag{9}$$

The investment cost, embodied energy, and embodied carbon can be estimated from real-life inventory data.

$$E_{CO}^{inv} = e_{CO,WI}^{inv}X_{WI} + e_{CO,RI}^{inv}X_{RI} + e_{CO,WT}^{inv}X_{WT} + e_{CO,SH}^{inv}X_{SH} + e_{CO,BB}^{inv}X_{BB} + e_{CO,CHP}^{inv}X_{CHP} + e_{CO,PV}^{inv}X_{PV} \tag{10}$$
$$E_{EN}^{emb} = e_{EN,WI}^{emb}X_{WI} + e_{EN,RI}^{emb}X_{RI} + e_{EN,WT}^{emb}X_{WT} + e_{EN,SH}^{emb}X_{SH} + e_{EN,BB}^{emb}X_{BB} + e_{EN,CHP}^{emb}X_{CHP} + e_{EN,PV}^{emb}X_{PV} \tag{11}$$
$$E_{CE}^{emb} = e_{CE,WI}^{emb}X_{WI} + e_{CE,RI}^{emb}X_{RI} + e_{CE,WT}^{emb}X_{WT} + e_{CE,SH}^{emb}X_{SH} + e_{CE,BB}^{emb}X_{BB} + e_{CE,CHP}^{emb}X_{CHP} + e_{CE,PV}^{emb}X_{PV} \tag{12}$$

The recyclable energy and carbon are determined by the recycle ratio of each retrofitting material.

$$E_{EN}^{rec} = e_{EN,WI}^{emb}X_{WI}R_{EN,WI} + e_{EN,RI}^{emb}X_{RI}R_{EN,RI} + e_{EN,WT}^{emb}X_{WT}R_{EN,WT} + e_{EN,SH}^{emb}X_{SH}R_{EN,SH} + e_{EN,BB}^{emb}X_{BB}R_{EN,BB} + e_{EN,CHP}^{emb}X_{CHP}R_{EN,CHP} + e_{EN,PV}^{emb}X_{PV}R_{EN,PV} \tag{13}$$
$$E_{CE}^{rec} = e_{CE,WI}^{emb}X_{WI}R_{CE,WI} + e_{CE,RI}^{emb}X_{RI}R_{CE,RI} + e_{CE,WT}^{emb}X_{WT}R_{CE,WT} + e_{CE,SH}^{emb}X_{SH}R_{CE,SH} + e_{CE,BB}^{emb}X_{BB}R_{CE,BB} + e_{CE,CHP}^{emb}X_{CHP}R_{CE,CHP} + e_{CE,PV}^{emb}X_{PV}R_{CE,PV} \tag{14}$$

The electricity energy production from PV panel Q_{PV} and wind turbine Q_{WT} is determined by their design area, design power, actual solar radiation, outdoor air dry-bulb temperature and wind speed. The heating energy from the solar heater Q_{SH} is decided by its design area and actual solar radiation. The CHP system is operated by following electricity strategy. In other words, the operating power of CHP system $Q_{CHP,e}$ is determined by the actual electricity demand, while its additional heat is recovered for heating supply. If the heating supply is smaller than the heating demand, biomass boiler Q_{BB} and original gas boiler Q_{GB} would be operated respectively. If the electricity supply is smaller than the electricity demand, electricity would be imported from the power grid Q_{PG}. The flow chart in Fig. 3 illustrates the control algorithm of the integrated energy system. It is assumed that excessive heat and electricity is not allowed to be fed back to the heat and power grid. Therefore, the consumption rate of natural gas Q_{ng}^{post}, electricity Q_{ele}^{post} and biomass Q_{bio}^{post} can be determined:

$$Q_{ng}^{post} = \frac{Q_{GB}}{\eta_{gb}} \tag{15}$$

$$Q_{ele}^{post} = Q_{PG} \tag{16}$$

$$Q_{bio}^{post} = \frac{Q_{BB}}{\eta_{BB}} + \frac{Q_{CHP,e}}{\eta_{CHP,e}} \tag{17}$$

Meanwhile, three performance indicators, namely, unit return cost P_{CO}, unit return energy P_{EN} and unit return carbon P_{CE} are proposed to evaluate the economic, energetic and environmental performance of the retrofitting options. The unit return cost indicates the required investment cost to get the unit cost saving.

$$P_{CO} = E_{CO}^{inv}/\Delta E_{CO} \tag{18}$$

The unit return energy indicates the required embodied energy to get the unit energy reduction.

$$P_{EN} = E_{CO}^{inv}/\Delta E_{EN} \tag{19}$$

The unit return carbon indicates the required embodied carbon to get the unit carbon emission reduction.

$$P_{CE} = E_{CO}^{inv}/\Delta E_{CE} \tag{20}$$

2.3 Optimisation constraints

Due to the limitation of the building site, off-site renewable energy is not allowed. Thus, the total area of PV panel and the solar heater should not be larger than the roof area. Meanwhile, the surface area of wall insulation and the surface area of roof insulation should not be larger than the total external wall area and total roof area, respectively. Moreover, to avoid energy waste during the energy valley period, the design power of the window turbine, CHP system and biomass boiler is no larger than 50 kW, 50 kW and 200 kW, respectively. The value range of each decision variable is summarised in Table 2.

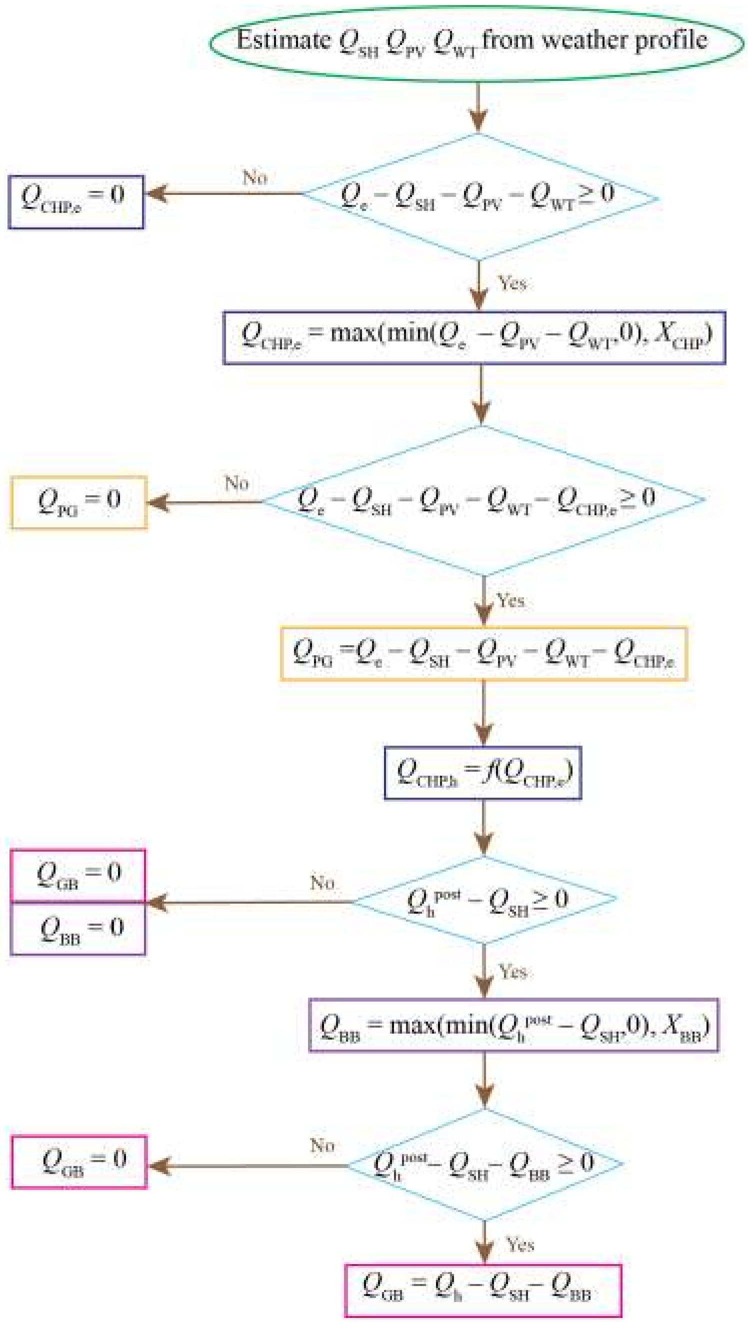


Fig. 3. The control algorithm of the retrofitted integrated energy system.

Table 2. Summary of design variables and constraints

Design variables	Symbol	Constraints
Design area of roof insulation	X_{RI}	$X_{RI} \leq S_{roof}$
Design area of wall insulation	X_{WI}	$X_{WI} \leq S_{wall}$
Design power of wind turbine	X_{WT}	$X_{WT} \leq$ 50 kW
Design area of solar heater	X_{SH}	$X_{SH} + X_{PV} \leq S_{roof}$
Design area of PV panel	X_{PV}	
Design power of CHP system	X_{CHP}	$X_{CHP} \leq$ 50 kW
Design power of biomass boiler	X_{BB}	$X_{BB} \leq$ 200 kW

2.4 Optimisation algorithm

Particle swarm optimisation (PSO) has been broadly adopted to handle sophisticated engineering problems [20]. The main advantages of PSO are its high learning speed and less computation consumption. In PSO, each particle represents a single solution with its position and velocity. For the retrofitting optimisation problem, the position of each solution *k* is encoded in an $m \times n$ matrix $\mathbf{X}_k$, where *m* is the number of options of each decision variable while *n* is the number of decision variables (i.e. 7 in this study). The velocity of each particle is also considered as an $m \times n$ matrix V_k, and $V_k(i,j) \in [-V_{max}, V_{max}]$ $(\forall i,j), i \in \{1,2,\dots,m\}, j \in \{1,2,\dots,n\}$.

The position is evaluated by the optimisation objective function, while the velocity indicates the moving direction of the particle. The particles move in the problem space by following the current optimal particles. After initialisation by a group of random particles, PSO searches for the optimal values through updating generations. In each iteration, each particle is updated by the values of the particle's best value *pbest* and particle's global best value *gbest*. The *pbest* is the best solution the individual particle has achieved, while the *gbest* is the global best solution obtained by all the particles so far [21].

$$V_k^{t+1}(i,j) = \gamma_1 V_k^t(i,j) + c_1\gamma_2\left(pbest_k^t(i,j) - \mathbf{X}_\mathbf{k}^\mathbf{t}(i,j)\right) + c_2\gamma_3\left(gbest_k^t(i,j) - \mathbf{X}_\mathbf{k}^\mathbf{t}(i,j)\right) \tag{21}$$

$$\mathbf{X}_\mathbf{k}^\mathbf{t+1}(i,j) = \mathbf{X}_\mathbf{k}^\mathbf{t}(i,j) + V_k^{t+1}(i,j) \tag{22}$$

where γ_1, γ_2 and γ_3 represents the inertia weight, cognitive parameter and social parameter, respectively. c_1 and c_2 are random values in the range of [0, 1] generated for each velocity update.

3. **Material and research methods**

A real-life office building is adopted to evaluate the performance of the proposed data-driven life-cycle retrofitting optimisation approach. To allow the work to be reproduced by an independent researcher, the details of this case study is introduced. It includes detailed building information, simulation models of retrofitting options, historical weather profile, historical building energy demand, estimated renewable energy production and inventory data.

3.1 General building information

Costain House is a representative high-rise office building in Europe. It is located at Maidenhead, United Kingdom and is adopted in this case study. Costain House is a three-floor office building with a floor area of 1133 m^2 and an external wall area of 585 m^2. It is a Z-shape building. The outlook of the building is shown in Fig. 4, while the floor plan is shown in Fig. 5. The general occupancy number is 60 for each floor, with a fresh air requirement of 10L/s/person. At the current state, it is heated using traditional gas heating and fan coils. The full building energy management system is deployed and operated. Lighting is provided using combinations of LED and Strip FL. Good lighting is generally provided with a large window area. The infiltration rate is 0.2, and the indoor design temperature is 24 °C. Floor-foam insulation has already been installed on each floor to reduce heat loss through the ground. Double-glazing windows have also been installed to minimise noise and heat loss through cold outdoor air.

Fig. 4. Costain House.

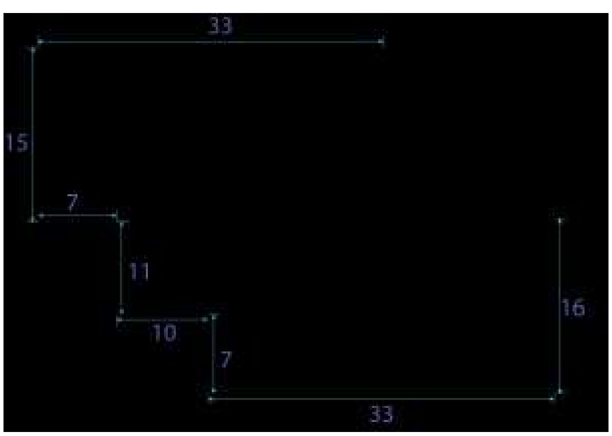


Fig. 5. Floor plan of Costain House.

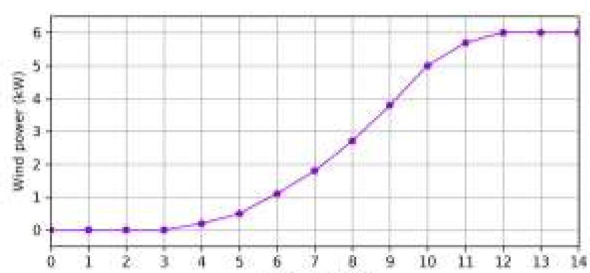


Fig. 6. Performance map of the wind turbine.

3.2 Retrofitting options and simulation model

As introduced in Section 2, the investigated retrofitting options include roof insulation, wall insulation, wind turbine, solar heater, biomass boiler, CHP system and PV panel. The thermodynamic model and technical parameters of different retrofitting options are summarised in Tables 3 and 4, respectively. The first principle of heat conduction and convection is adopted to investigate the energy-saving performance of wall and roof insulation [22]. Meanwhile, previously developed thermodynamic models of solar heater [23], biomass boiler [24], biomass-driven CHP system [25], PV panel [26], and practical performance data of wind turbine [27] are adopted to obtain the year-round renewable energy production and assess their energy-saving ability. It is assumed that the excess electricity and heating energy cannot be fed back to the electricity and heat grid.

Table 3. Thermodynamic model of each retrofitting option.

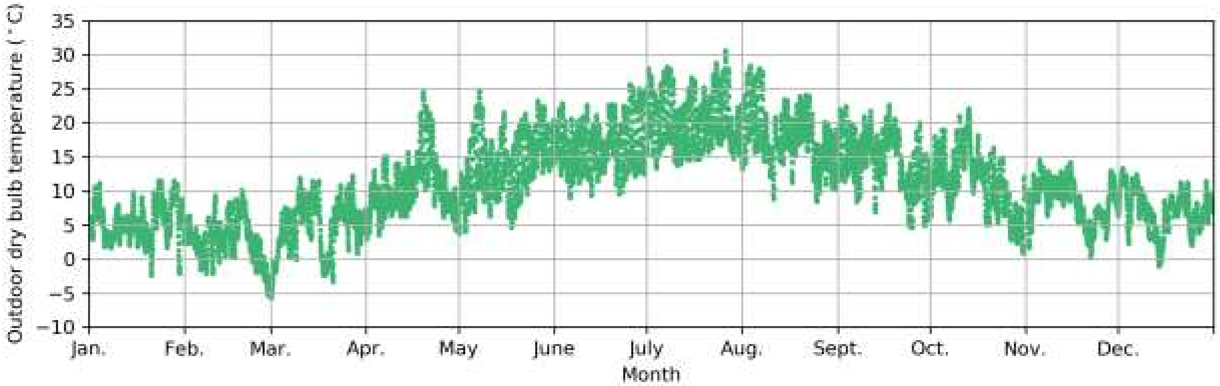
Roof insulation	$Q_{trans,roof} = U_{roof}A_{roof}CLTD_{roof}$
Wall insulation	$Q_{trans,wall} = U_{wall}A_{wall}CLTD_{wall}$
Solar heater	$Q_{SH} = G \cdot A_{SH} \cdot \eta_{SH}$ $\eta_{SH} = \eta_{SH,n} - \alpha \times (T_{DB} - T_{SH,ref})/G$
Biomass boiler	$q_{Boiler,pr,h} = q_{Boiler,co}\eta_{Boiler,h}$
CHP system	$q_{CHP,e} = q_{CHP,co}\eta_{CHP,e}$ $q_{CHP,h} = q_{CHP,co}\eta_{CHP,h}$
PV panel	$Q_{PV} = G \cdot A_{PV} \cdot \eta_{PV}$ $\eta_{PV} = \eta_{PV,n}[1 + \varepsilon_T(T_{db} - T_{PV,ref})][1 + \varepsilon_\varphi(G - G_{PV,ref})]$
Electricity storage	$E_{ES,j+1} = E_{ES,j} + r_{ch,ES}\eta_{ch,ES} - r_{dch,ES}/\eta_{dch,ES}$
Heat storage	$E_{HS,j+1} = E_{HS,j} + r_{ch,HS}\eta_{ch,HS} - r_{dch,HS}/\eta_{dch,HS}$

Table 4. Parameters of different retrofitting options.

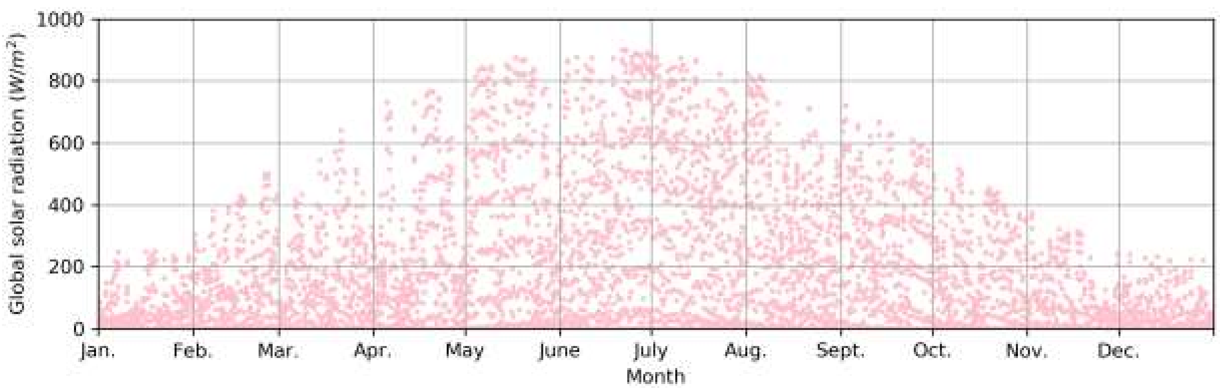
Roof insulation [28]	U-value of roof U_{roof} (W/m^2)	Pre-retrofitting	2.45
		Post-retrofitting	0.251
Wall insulation [28]	U-value of wall U_{wall} (W/m^2)	Pre-retrofitting	2.45
		Post-retrofitting	0.256
Wind turbine [27]	Performance map		Fig. 6
Solar heater [29]	Nominal efficiency (%)		44
Biomass boiler [30]	Efficiency (%)		92
CHP system [31]	Electrical efficiency (%)		18
	Thermal efficiency (%)		72
PV panel [32]	Nominal efficiency $\eta_{BIPV,n}$ (%)		12
	Reference temperature T_{ref} (°C)		25
	Reference radiation (kJ/h m^2)		3600
	Correction coefficient of temperature ε_T		-0.005
	Correction coefficient of solar radiation ε_φ		0.000025
Electricity storage [33]	Charging efficiency (%)		90
	Discharging efficiency (%)		90
Heat storage [33]	Charging efficiency (%)		90
	Discharging efficiency (%)		90

3.3 Historical weather condition

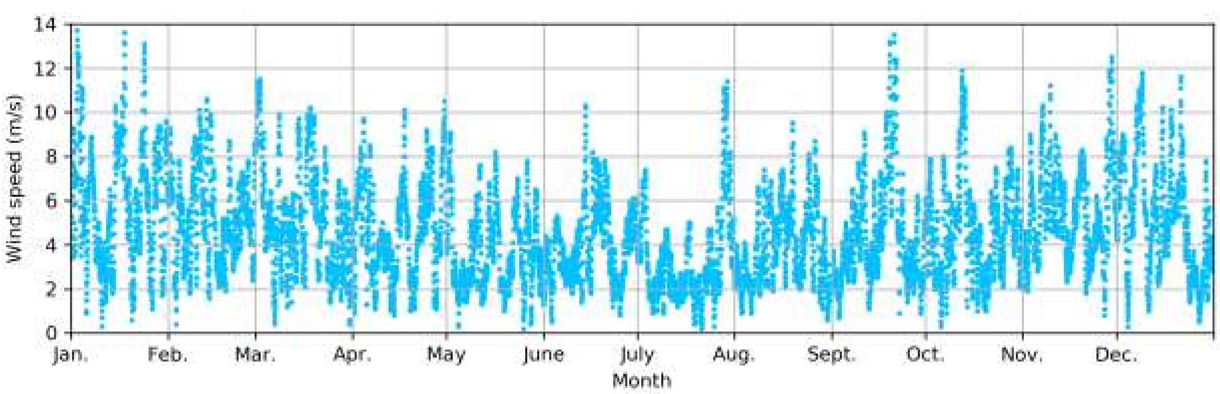
The year-round historical weather data in 2018 is collected from the local weather station near Maidenhead weather station. According to Table 1, the weather profiles play an important role in determining building energy demand and renewable energy production. The three most important weather conditions are outdoor air dry-bulb temperature, global solar radiation, and wind speed, as summarised in Fig. 7.



(a) Outdoor dry-bulb temperature



(b) Global solar radiation



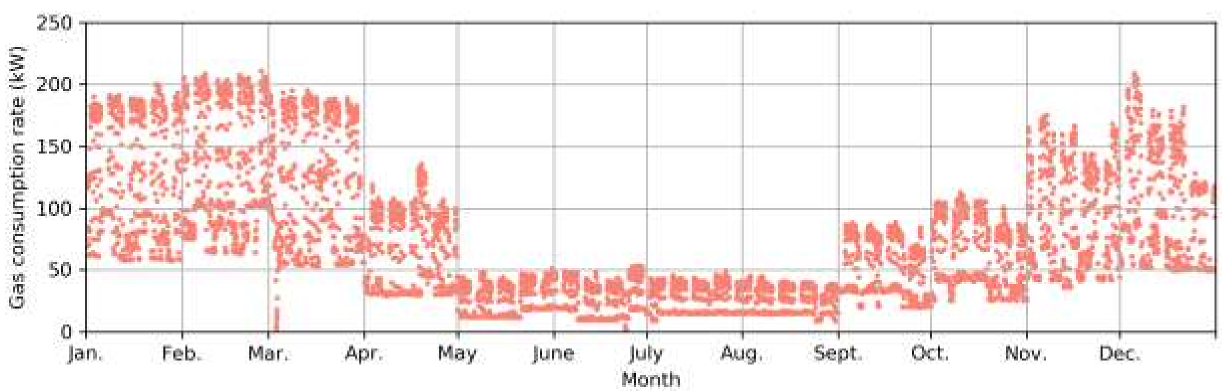
(c) Wind speed

Fig. 7. Outdoor weather profile.

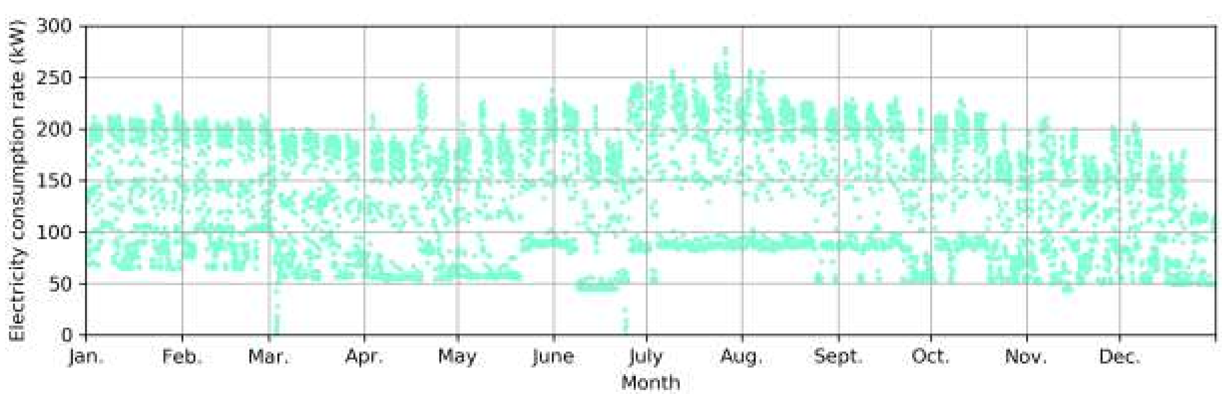
3.4 Building energy demand

According to the historical gas and electricity consumption profile, the year-round gas and electricity consumption is 568838 kWh and 1015478 kWh in 2018, respectively. The peak gas and electricity consumption is 211 kW and 279 kW, respectively. The relatively high gas consumption is mainly due to the high window-to-wall ratio (i.e. 2), while the relatively high electricity consumption owes to the high-rise computing servers. The hourly and monthly gas and electricity consumption is shown in Fig. 8.

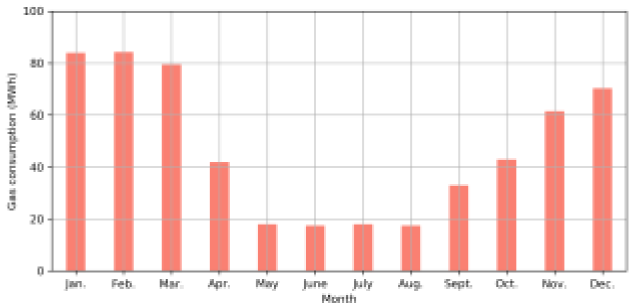
- The high gas consumption is identified during January to March, November and December, mainly due to its low outdoor air dry-bulb temperature and solar radiation. During those periods, the gas consumption is between 50 and 211 kW. On the contrary, the lowest gas consumption is found during May to September, owing to the relatively high outdoor air dry-bulb temperature and high solar radiation. During this period, the gas consumption is between 0 and 50 kW.
- Compared to gas consumption, electricity consumption is relatively constant throughout the whole year. The monthly electricity consumption is between 69000 kWh and 99242 kWh. However, the relatively high value is experienced during July and August. During these two months, the electric chiller is turned on for cooling purpose, which results in higher electricity consumption.



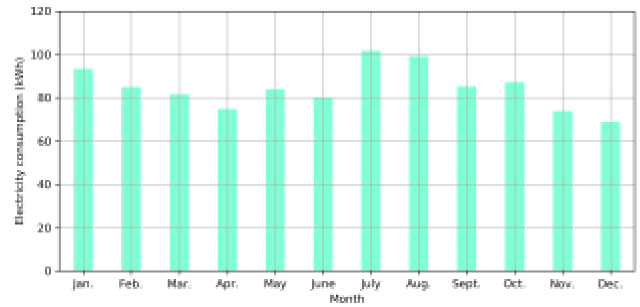
(a) Hourly gas consumption rate



(b) Hourly electricity consumption rate



(c) Monthly gas consumption

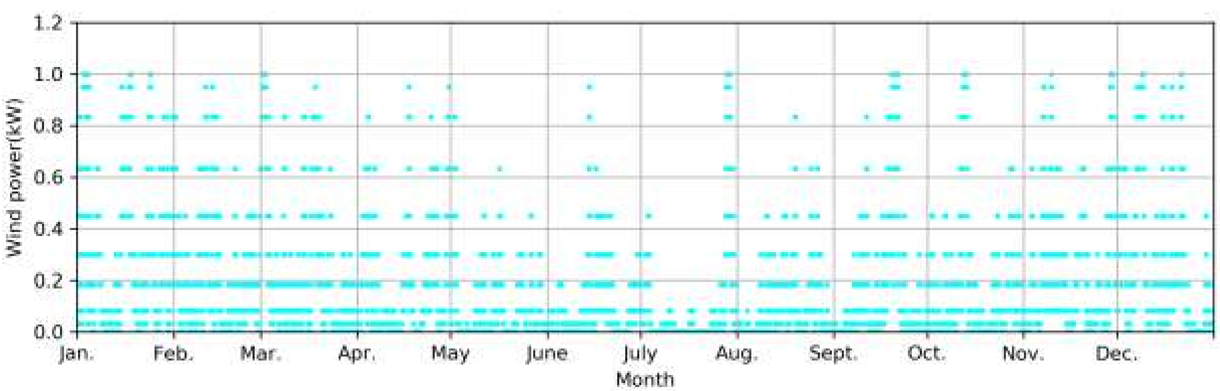


(d) Monthly electricity consumption

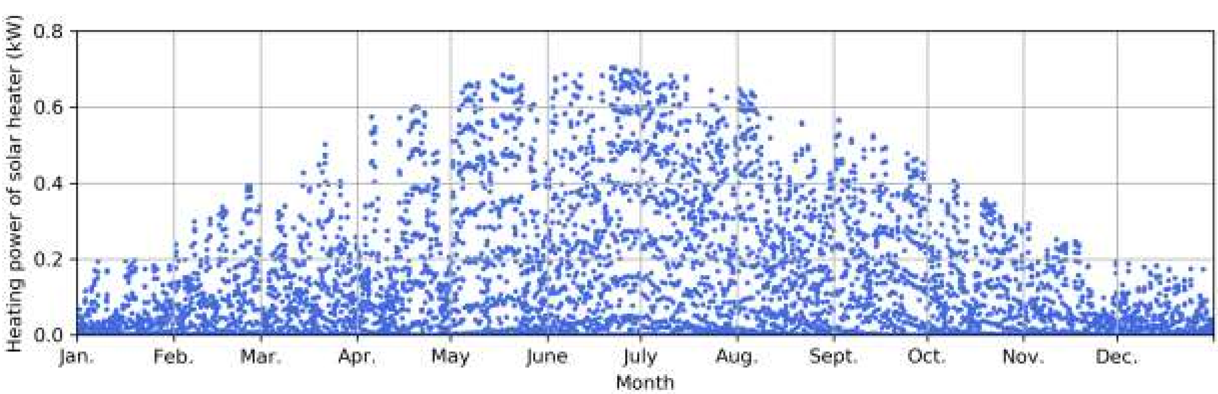
Fig. 8. Year-round gas and electricity consumption.

3.5 Renewable energy production

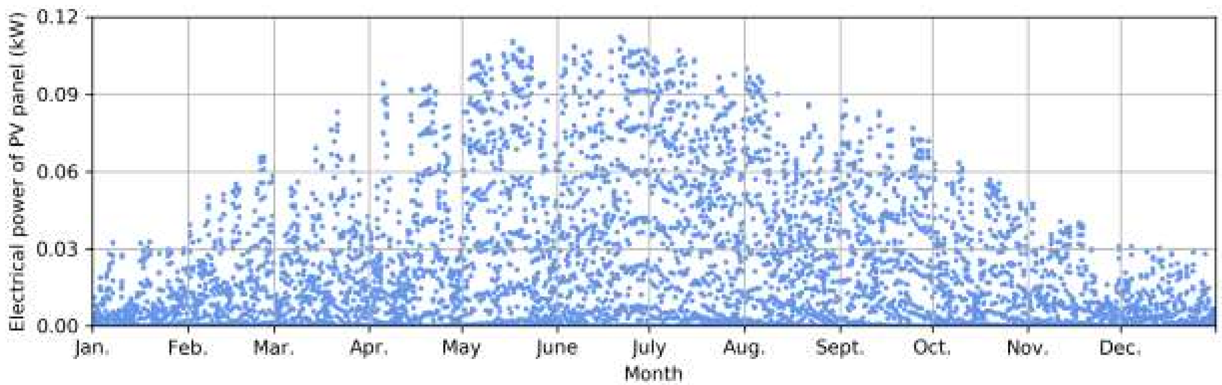
The energy production potential of the wind turbine, solar heater and PV panel is investigated using the year-round weather data in 2018, as shown in Fig. 9 and Table 5. The year-round energy production is evaluated based on a 1 kW wind turbine, 1 m^2 solar heater and 1 m^2 PV panel, respectively.



(a) Electricity production from 1 kW wind turbine



(b) Thermal production from 1 m^2 solar heater



(c) Electricity production from 1 m^2 PV panel

Fig. 9. Year-round energy production from the wind turbine, solar heater and PV panel.

Table 5. Peak and year-round total energy production and demand.

	Peak (kW)	Year-round total energy production or demand(kWh)
Wind turbine	1	1502
Solar heater	0.7056	876
PV panel	0.1122	138

3.6 Inventory data

ISO 14,040 standard was followed in data collection for life cycle inventory development [34]. The embodied energy and carbon refers to the primary energy consumption and carbon emission during the production of retrofitting materials (i.e. from raw material extraction to final manufacturing). The inventory data is collected from various sites in the UK to replicate the real-world situation, as summarised in Table 6.

Table 6. Summary of inventory data for various retrofitting materials.

Item	Cost (£)	Embodied energy (MJ)	Embodied carbon (kg)	Recycle ratio	Life-time (year)
Electricity from power grid (per kWh) [35, 36]	0.1453	9.0	0.59	-	-
Biomass (per kWh) [35, 37, 38]	0.0126	0.455	0.01563	-	-
Natural gas (per kWh) [35, 39]	0.028	3.6	0.18385	-	-
Roof insulation with sheep wool (per m^2) [40-42]	6.8	28	1.8	0.9	60
Wall insulation with the wood board (per m^2) [40-42]	10.5	40	0.98	0.5	60
PV panel (per m^2) [43, 44]	219	3266.6	157.8	0.3	25
Wind turbine (per kW) [45, 46]	1000	72380	8671.2	0.2	20
Solar heater (per m^2) [47, 48]	38	1520.73	120.05	0.1	20
CHP system (per kW) [49]	1750	138800	5920	0.1	15
Biomass boiler (per kW) [50]	78	57005.2	471	0.2	20

4. Results and discussion

In the beginning, the decarbonisation evaluation and life-cycle performance of each single retrofitting measure is evaluated. Secondly, the parametric analysis of the design area of solar heater and PV panel, as well as the design power of wind turbine and CHP system is conducted. Meanwhile, the parametric analysis of the capacity of electricity storage and heat storage is also conducted. Finally, the optimal retrofitting plan under each optimisation objective is presented, along with its corresponding life-cycle performance.

4.1 Decarbonisation evaluation and life-cycle performance of each retrofitting option

The life-cycle cost, energy and carbon of each retrofitting option are summarised in Fig. 10, along with the corresponding performance of the original building without taking any retrofitting measures. As shown in Table 6, the life-time is different among various retrofitting options. Thus, the life-cycle cost, energy and carbon of the pre-retrofitting building are evaluated at different life span. For each retrofitting option, the manufacturing of retrofitting materials would result in increased cost, energy and carbon at the beginning of the life cycle. These are generally regarded as investment cost, embodied energy and embodied carbon, respectively.

The U-value of the envelope and building heating demand can be decreased through roof insulation and wall insulation. Electricity can be generated from wind and solar energy using wind turbine and PV panel, respectively. Thermal energy can be converted from solar energy using solar panel. Meanwhile, CHP system can enhance overall energy efficiency by simultaneously generating electrical and thermal energy. To generate the same amount of thermal energy, biomass boiler consumes less primary energy than that of conventional gas boiler. Due to the energy-saving performance from each retrofitting option, the economic cost, energy consumption and carbon emission during the building operating stage would be decreased.

Moreover, part of the embodied energy and carbon from the retrofitting materials can be recycled and reused at the end of its life. Therefore, by implementing the retrofitting options on existing buildings, the overall life-cycle economic cost, energy consumption and carbon footprint can be downgraded.

In this section, the design area of roof insulation, design area of wall insulation, design power of biomass boiler is fixed at the same value as the entire roof area, entire wall area and rated power of original gas boiler, respectively. On the other hand, the decarbonisation performance of wind turbine, solar heater, CHP system and PV panel is assessed at different design power or design area. It is found that the decarbonisation performance (i.e. life-cycle cost-saving, energy reduction and carbon reduction) enhances with the increase of design power and design area. For wind turbine, the optimal decarbonisation performance is identified when its rated power is 200 kW, while its performance downgrades with the further increase of rated power. The decarbonisation performance of each retrofitting option is summarised in Table 7. The 1133 m^2 PV panel results in the best performance in terms of life-time cost-saving, the 200 kW wind turbine results in the best performance in terms of life-time energy reduction, while the 100 kW CHP system results in the best performance in terms of life-time carbon reduction. On the contrary, the 585 m^2 of wall insulation results in the smallest life-time cost-saving, energy reduction and carbon reduction.

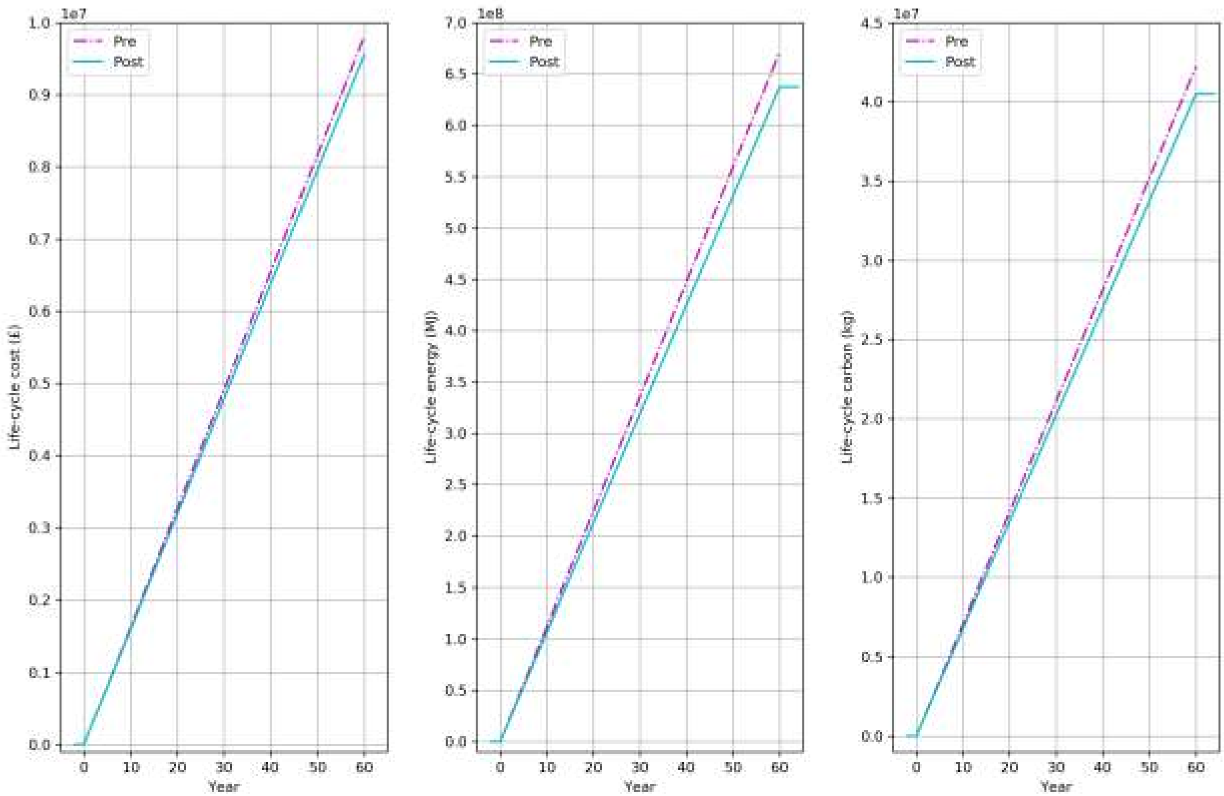
Table 7. Decarbonisation performance of each retrofitting option.

Retrofitting option		Roof insulation	Wall insulation	Wind turbine	Solar heater	Biomass boiler	CHP system	PV panel
Design size		1133 m^2	585 m^2	200 kW	1133 m^2	320 kW	100 kW	1133 m^2
Economy cost (£)	Pre-	9808587	9808587	3269529	3269529	3269529	2452147	4007273
	Post-	9555603	9708753	2709453	3183196	3119287	2291455	3306765
	Reduction	2.58%	1.02%	17.13%	2.64%	4.60%	6.55%	17.48%
Energy consumption (MJ)	Pre-	671227236	671227236	223742412	223742412	223742412	167806809	279678015
	Post-	637432463	657587125	180460938	207620079	202555833	145994116	239112781
	Reduction	5.03%	2.03%	19.34%	7.21%	9.47%	13.00%	14.50%
Environmental carbon emission (kg)	Pre-	42222780	42222780	14074260	14074260	14074260	10555695	17592825
	Post-	40495013	41525866	12179228	13305377	12281038	8911459	14874427
	Reduction	4.09%	1.65%	13.46%	5.46%	12.74%	15.58%	15.45%

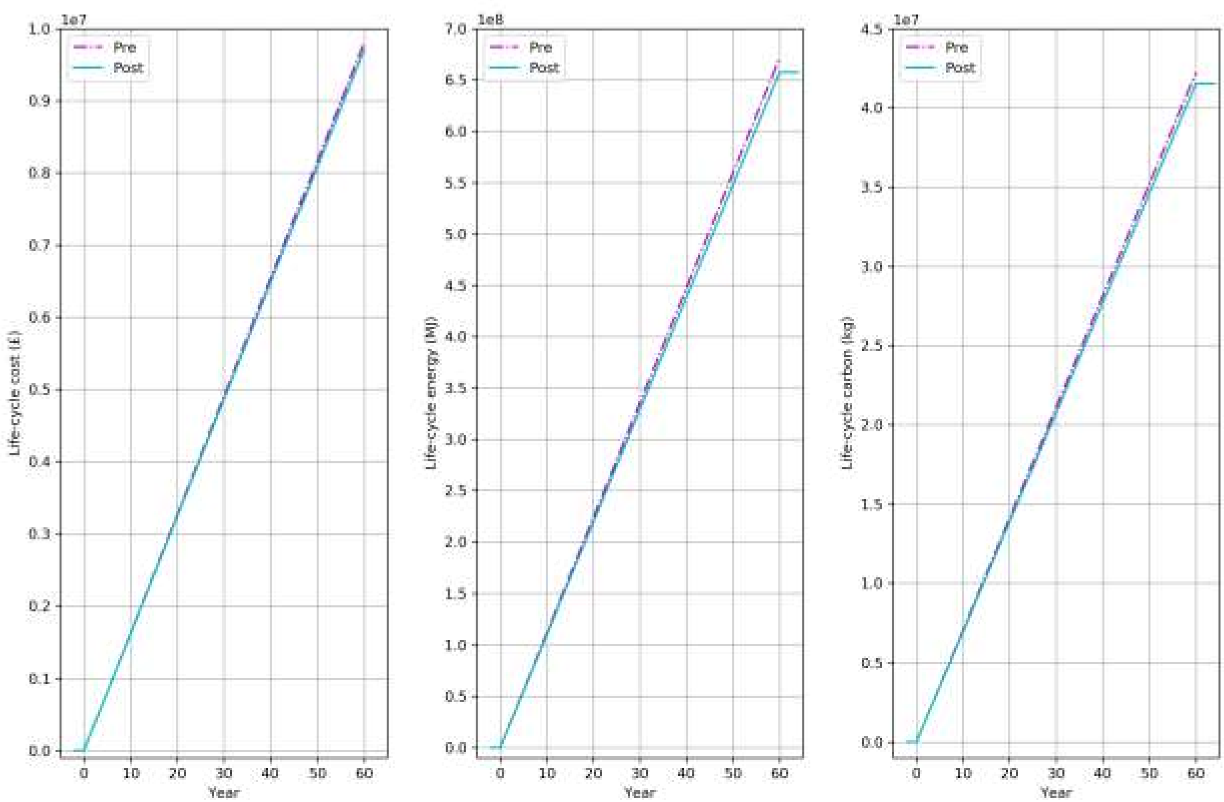
The unit return cost, energy and carbon of each retrofitting option at its design condition is summarised in Table 8. Unit return cost, energy and carbon indicate the amount of investment cost to get unit life-time cost-saving, life-time energy reduction and life-time carbon reduction, respectively. Wall and roof insulation has the smallest unit return cost (i.e. 0.061£/£), unit return energy (i.e. 0.445£/GJ), unit return carbon (i.e. 0.009£/kg), followed by solar heater, CHP system, biomass boiler, wind turbine and PV panel.

Table 8. Unit return cost, energy and carbon of each retrofitting option.

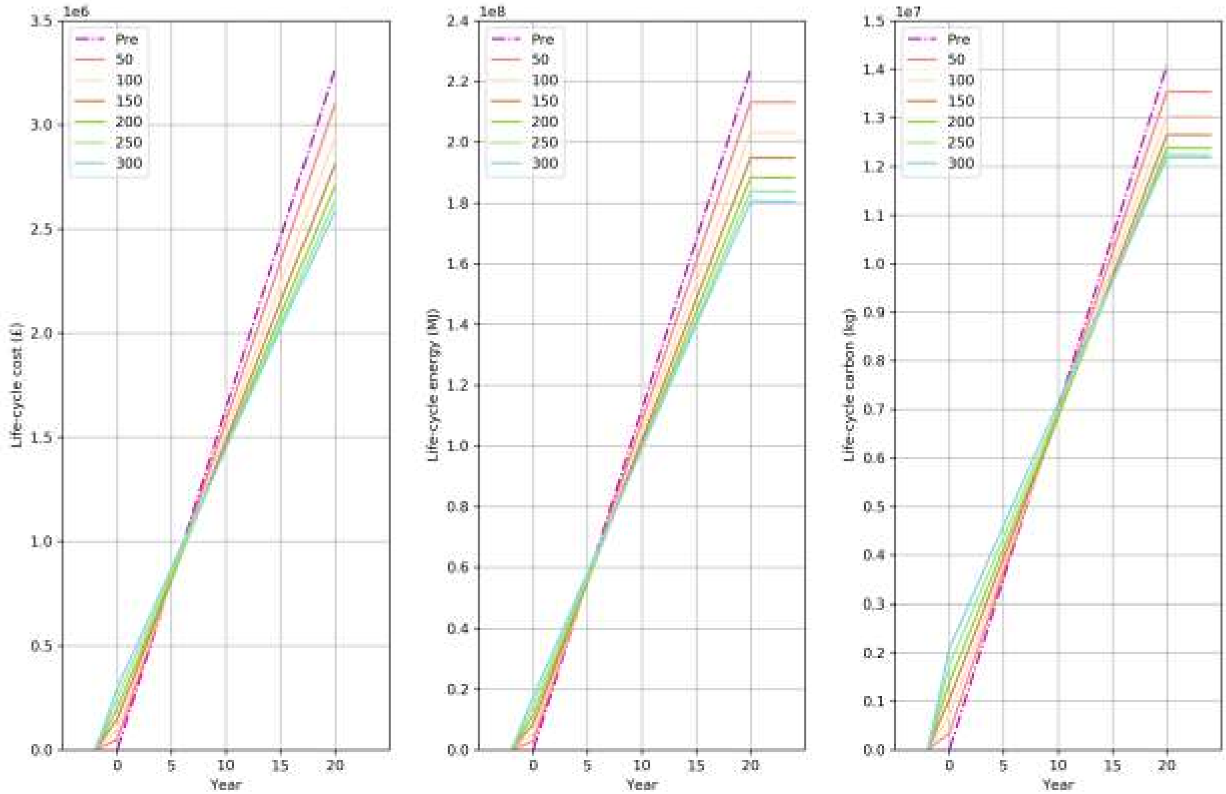
Performance indicator	Wall and roof insulation	Wind turbine	Solar heater	Biomass boiler	CHP system	PV panel
Unit return cost (£/£)	0.061	0.297	0.084	0.166	0.098	0.778
Unit return energy (£/GJ)	0.445	4.711	0.617	1.423	0.909	7.899
Unit return carbon (£/kg)	0.009	0.093	0.012	0.014	0.014	0.117



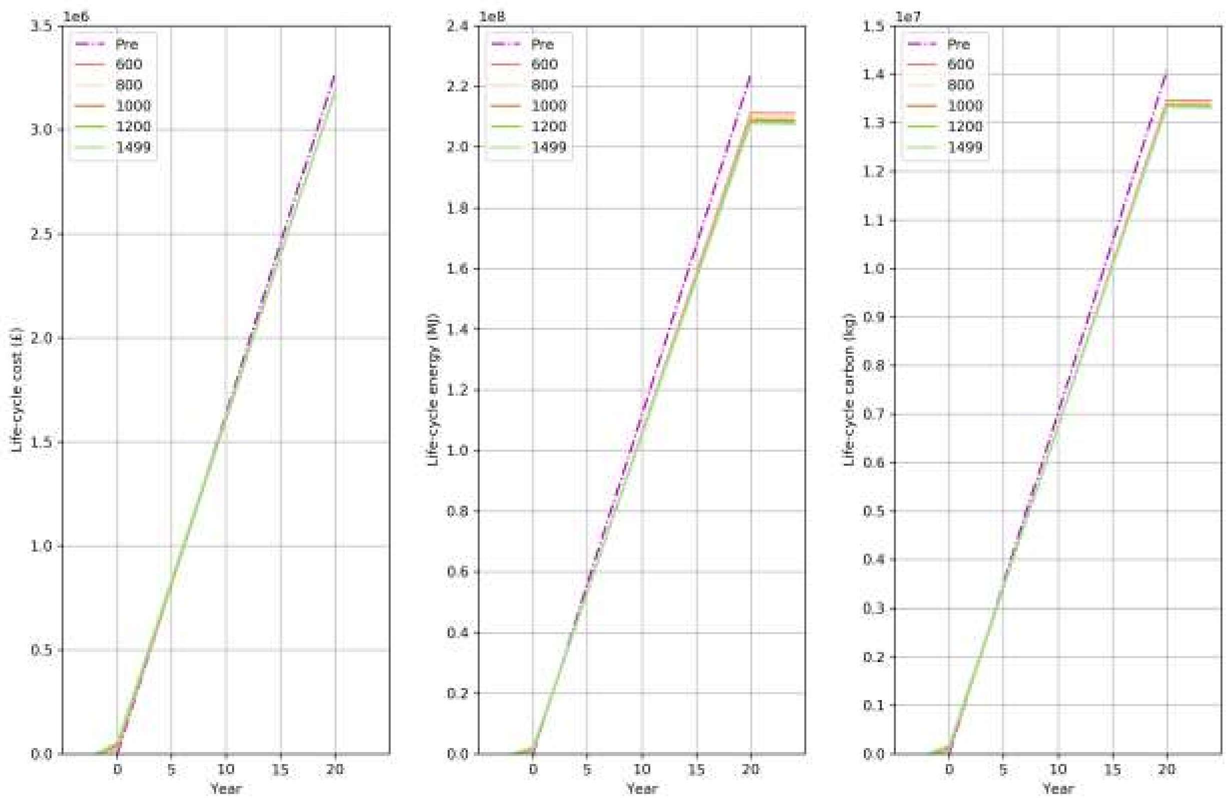
(a) Roof insulation



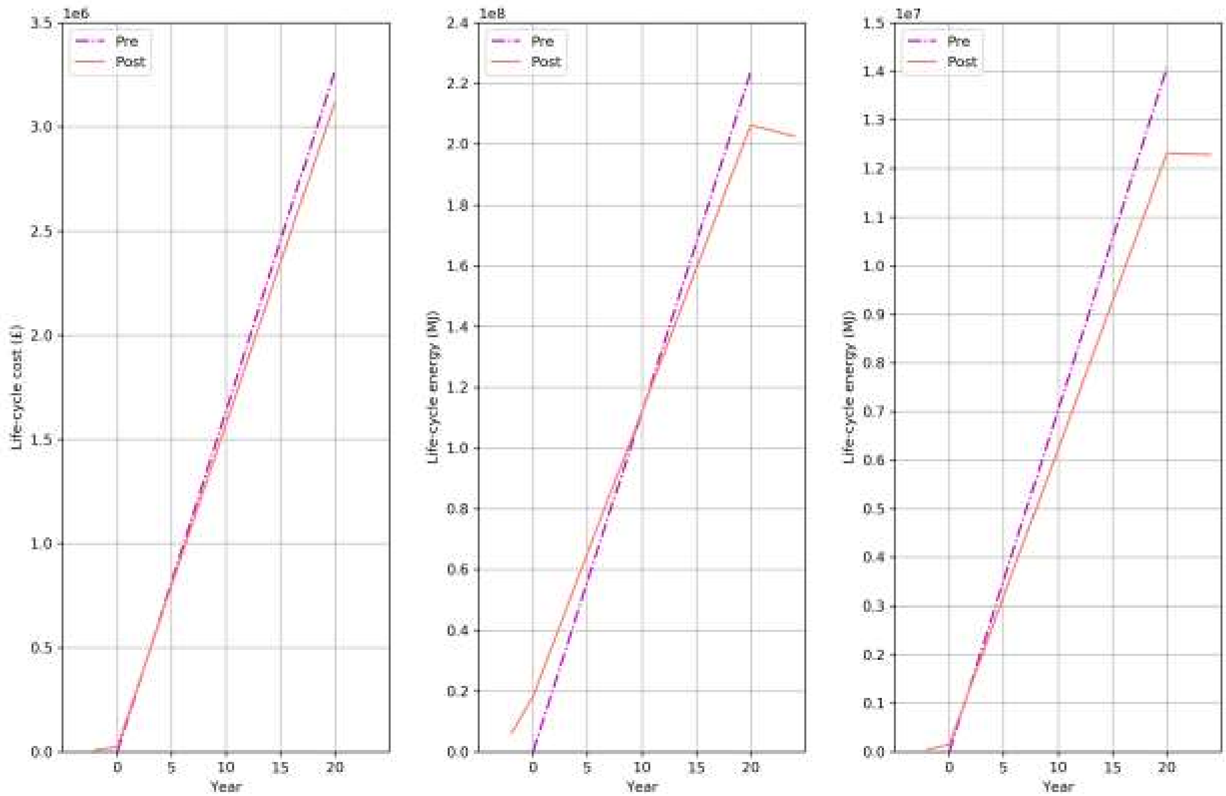
(b) Wall insulation



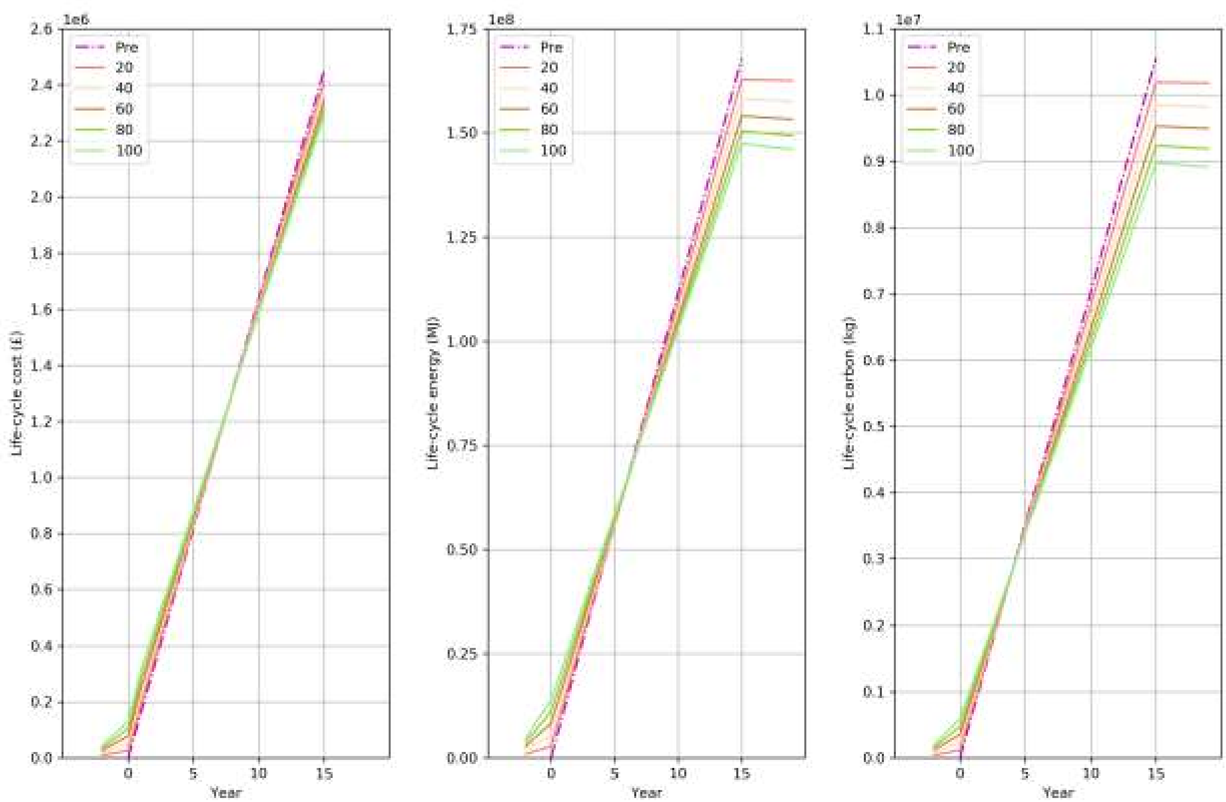
(c) Wind turbine



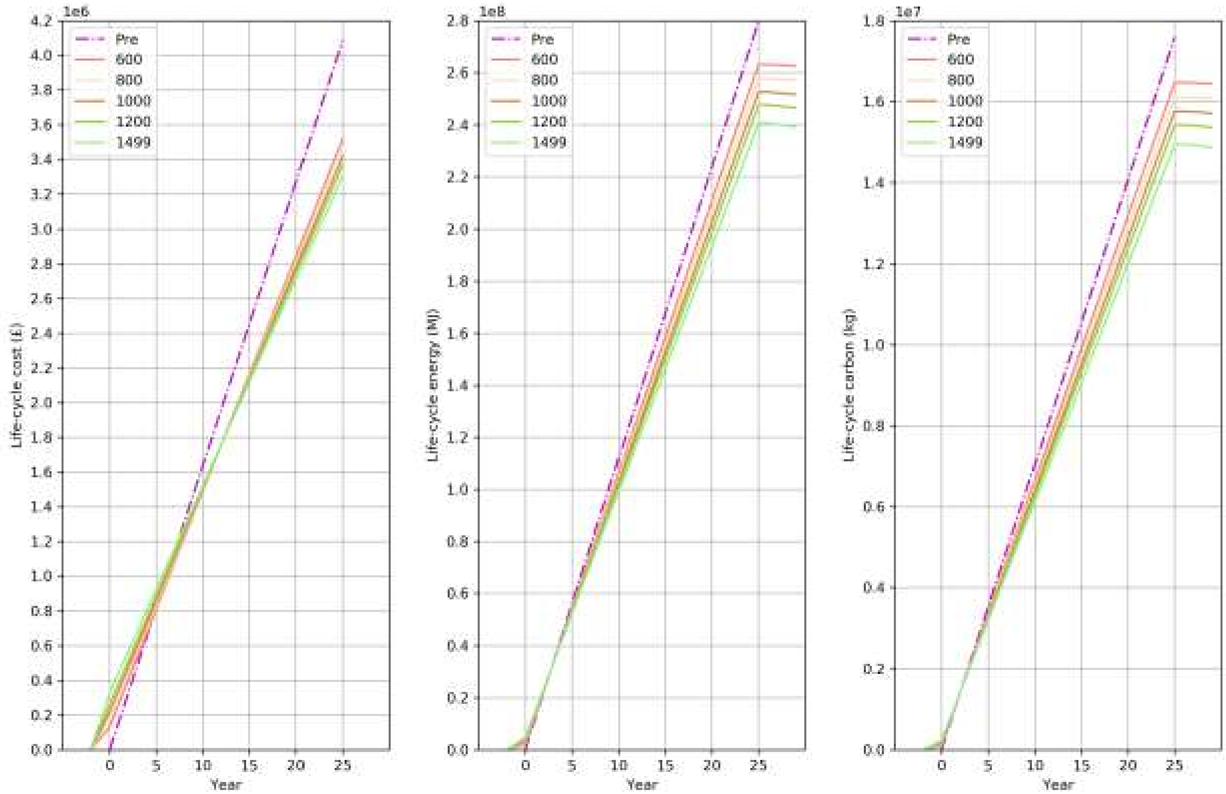
(d) Solar heater



(e) Biomass boiler



(f) CHP system



(g) PV panel

Fig. 10. Life-cycle cost, energy and carbon of each retrofitting option.

4.2 Decarbonisation performance evaluation at different rated power and design area

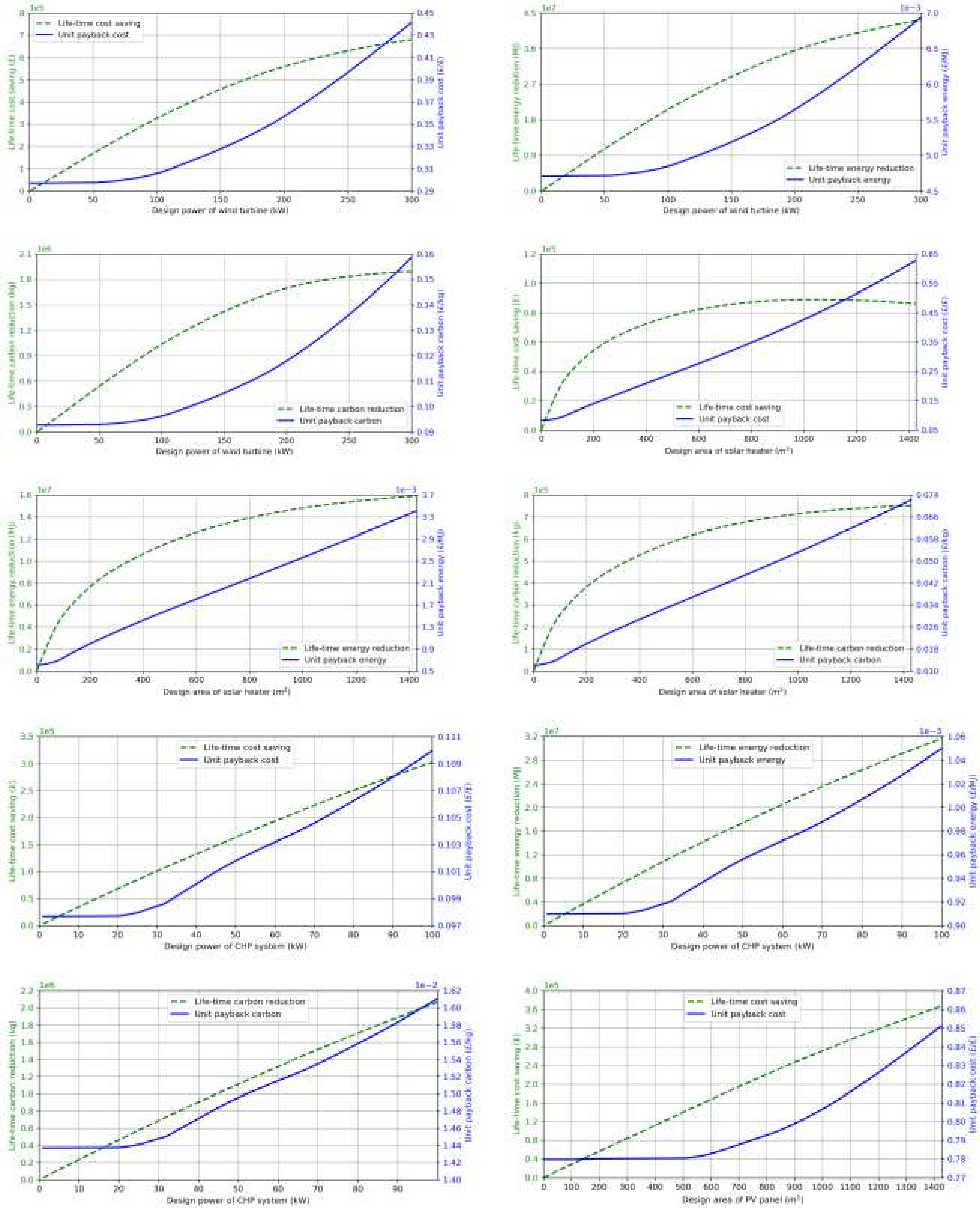
The life-time cost-saving, energy reduction and carbon reduction, along with unit return cost, unit return energy and unit return carbon of different configuration of wind turbine, solar heater, CHP system and PV panel is summarised in Fig. 11.

For the wind turbine, life-time cost-saving, energy reduction and carbon reduction increase with the increase of its design power. It is because the higher rated power of wind turbine can result in higher electrical energy production. Meanwhile, the unit return cost, energy and carbon are relatively constant at 0.297£/£, 4.711£/GJ and 0.093£/kg when the rated power of wind turbine is smaller than 50 kW. The unit return cost, energy and carbon increases with the increase of rated power when it is larger than 50 kW. It is because that the extra electricity generated by the wind turbine cannot be fed back to the power grid. However, the higher design power of wind turbine results in higher investment cost, embodied energy and embodied carbon.

For the solar heater, the life-time cost-saving reaches the peak when its design area is 1000 m^2, while the life-time energy reduction and carbon reduction keep increasing with the increase of its design area. It is because that more thermal energy can be produced through a larger design area of solar heater. However, there exists excessive heating energy when its production from the solar heater is higher than the actual building heating demand. Meanwhile, when the design area of the solar heater is smaller than 20 m^2, its unit return cost, energy and carbon are kept relatively constant around 0.084£/£, 0.617£/GJ and 0.012£/kg, respectively. The unit return cost, energy and carbon of solar heater keeps increasing with the increase of its design area when it is larger than 20 m^2. It is mainly due to the unbalance between solar heater production and building heating demand. In summer, the heating energy production from the solar heater is large due to high solar radiation, while building heating demand is small owing to low outdoor dry bulb temperature. Thus, there exists plenty of excessive heating energy production.

For the CHP system, the decarbonisation performance is evaluated on the principle of following electricity load strategy. In other words, the CHP system is primarily adopted to satisfy the building electrical energy demand, while the thermal energy from the prime mover is recovered for heating energy supply. If the energy from the CHP system is not sufficient to satisfy building electricity and heating demand, the conventional power grid and the gas heater would be adopted, respectively. As the peak electricity and heating demand is 279 kW and 211 kW, life-time cost-saving, energy reduction and carbon reduction steadily increase with the increase of design power of CHP system when it is smaller than 100 kW. Meanwhile, when the design power of the CHP system is smaller than 25 kW, its unit return cost, energy and carbon are kept relatively constant around 0.098 £/£, 0.909 £/GJ and 0.0144£/kg, respectively. The unit return cost, energy and carbon increase when the design power of the CHP system is larger than 25 kW, mainly due to the excessive heating and electricity supply from the CHP system.

For the PV panel, life-time cost-saving, energy reduction and carbon reduction steadily increase with the increase of its design area. It is because that larger electrical energy can be generated through a larger design area of the solar heater. Meanwhile, when the design area of the PV panel is smaller than 500 m^2, its unit return cost, energy and carbon are kept relatively constant around 0.7784 £/£, 7.899 £/GJ and 0.0144£/kg, respectively. It increases thereafter because electricity production from PV panel at its peak value is higher than the corresponding electricity demand.


Life-time cost saving
Unit payback cost
Life-time cost saving (£)
Unit payback cost (£/£)
Design power of wind turbine (kW)
Life-time energy reduction
Unit payback energy
Life-time energy reduction (MJ)
Unit payback energy (£/MJ)
Design power of wind turbine (kW)
Life-time carbon reduction
Unit payback carbon
Life-time carbon reduction (kg)
Unit payback carbon (£/kg)
Design power of wind turbine (kW)
Life-time cost saving
Unit payback cost
Life-time cost saving (£)
Unit payback cost (£/£)
Design area of solar heater (m²)
Life-time energy reduction
Unit payback energy
Life-time energy reduction (MJ)
Unit payback energy (£/MJ)
Design area of solar heater (m²)
Life-time carbon reduction
Unit payback carbon
Life-time carbon reduction (kg)
Unit payback carbon (£/kg)
Design area of solar heater (m²)
Life-time cost saving
Unit payback cost
Life-time cost saving (£)
Unit payback cost (£/£)
Design power of CHP system (kW)
Life-time energy reduction
Unit payback energy
Life-time energy reduction (MJ)
Unit payback energy (£/MJ)
Design power of CHP system (kW)
Life-time carbon reduction
Unit payback carbon
Life-time carbon reduction (kg)
Unit payback carbon (£/kg)
Design power of CHP system (kW)
Life-time cost saving
Unit payback cost
Life-time cost saving (£)
Unit payback cost (£/£)
Design area of PV panel (m²)

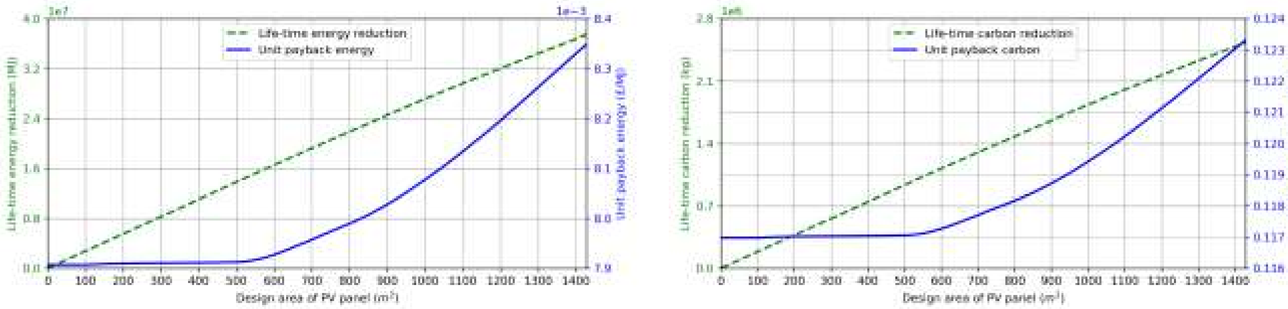


Fig. 11. Life-cycle performance at different design area and design power of each retrofitting option.

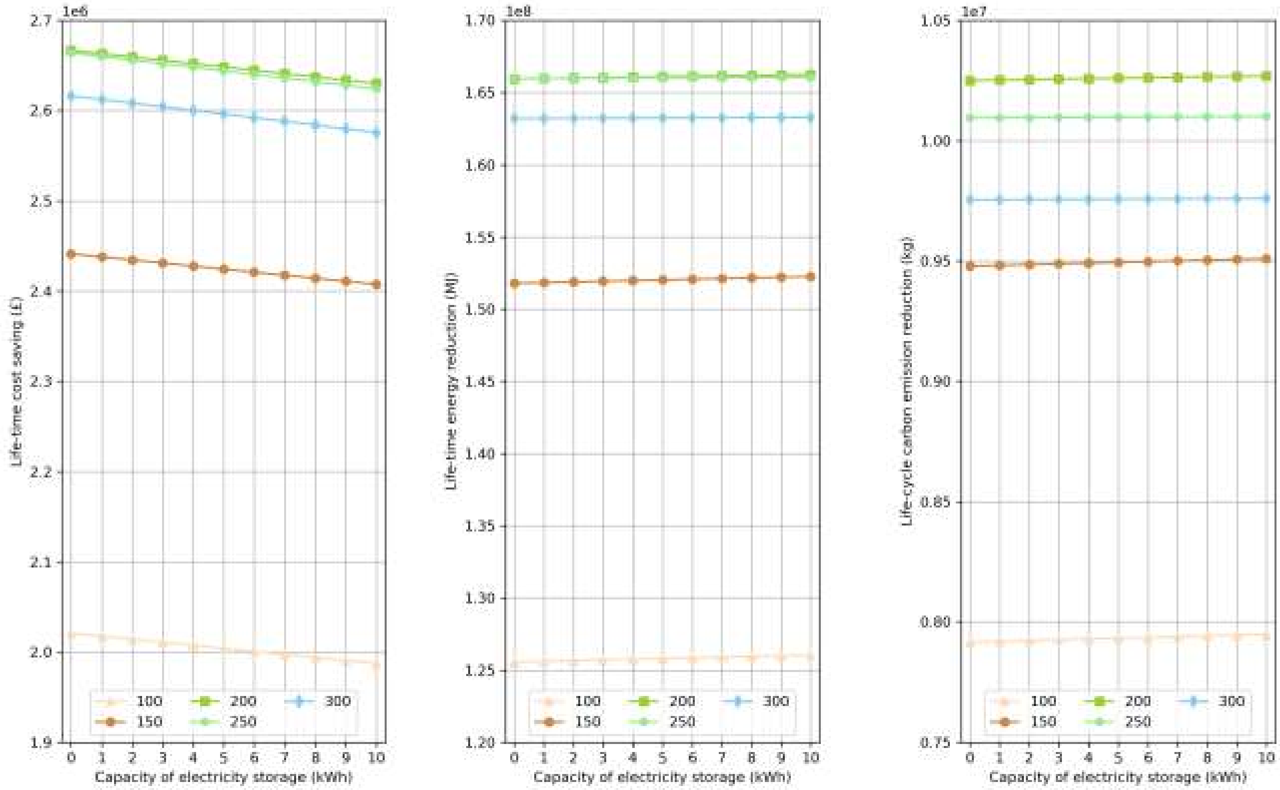
4.3 Effects of heat and electricity storage on its life-cycle performance

In Section 4.2, when the renewable energy production is higher than the actual energy demand, it is considered as excessive energy and wasted directly. To investigate the effects of energy storage in building retrofitting, the decarbonisation performance for electricity and heat storage integration is explored, as summarised in Fig. 12. Electricity and heat storage is adopted to store excessive electricity and heating energy. The stored energy can be discharged to help supply electricity and heating energy when renewable production is low.

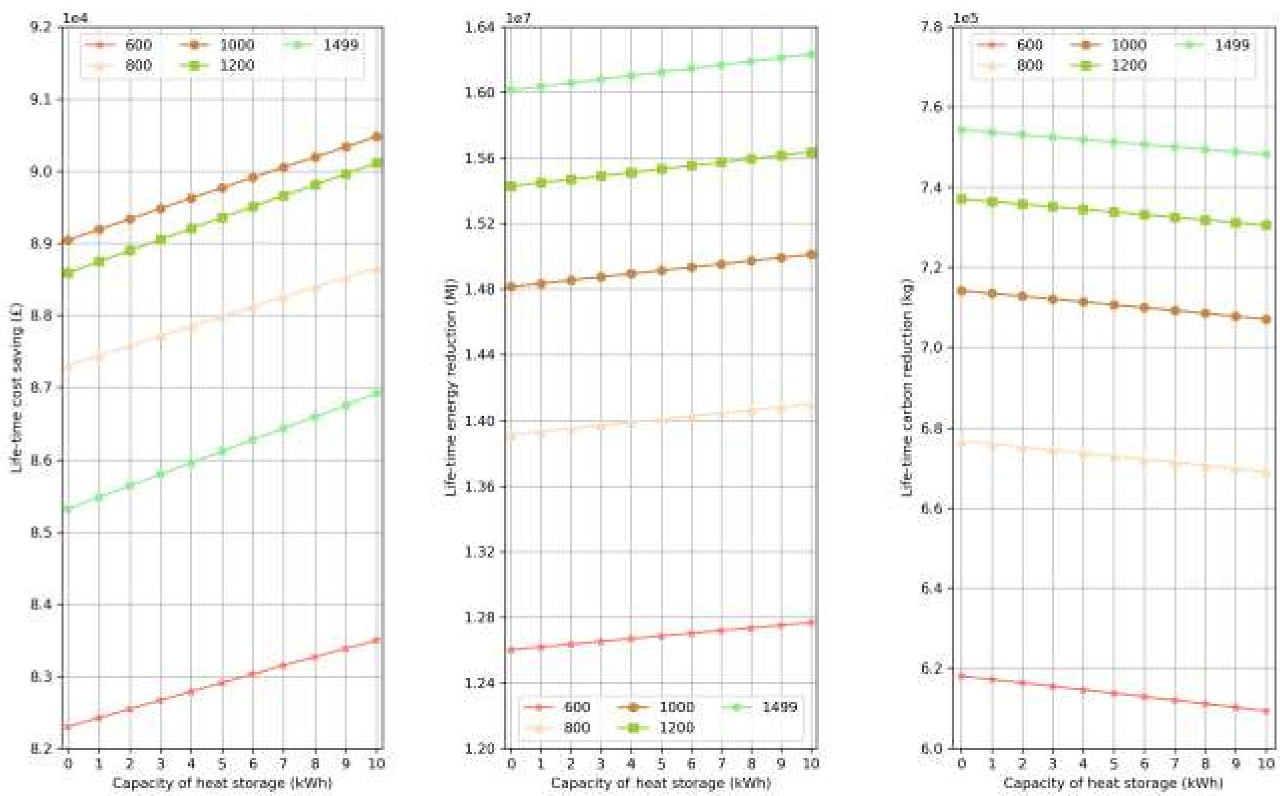
For the wind turbine, the life-time cost-saving decreases with the increased capacity of electricity storage. It indicates that the investment cost of electricity storage cannot be made up by its shifting ability for electricity demand. Meanwhile, there exists a slight increase in life-time energy reduction and carbon reduction with the increased capacity of electricity storage.

For the solar heater, the life-time cost-saving and energy reduction increases with the increased capacity of heat storage. It indicates that the investment cost and embodied energy of heat storage can be made up by its shifting ability for building heating demand. However, the life-time carbon reduction decreases with the increased capacity of heat storage. It means that the embodied carbon of heat storage cannot be made up of by its shifting ability of heating demand.

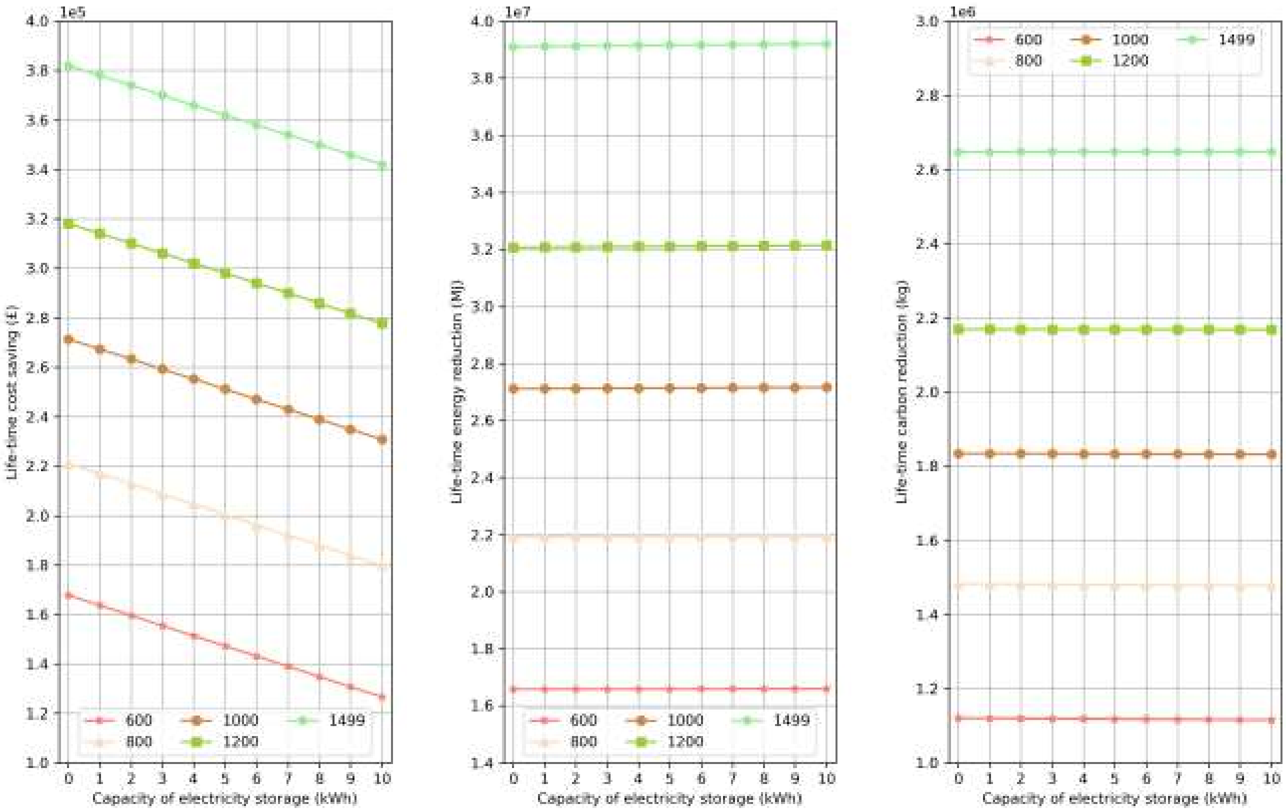
For the PV panel, the life-time cost-saving decreases with the increased capacity of electricity storage. It indicates that the investment cost of electricity storage cannot be made up by its shifting ability for PV panel electricity production and building electrical energy demand. Meanwhile, the life-time energy reduction and carbon reduction is almost constant at the different capacity of electricity storage.



(a) Wind turbine with electricity storage



(b) Solar heater with heat storage



(e) PV panel with electricity storage

Fig. 12. Life-cycle performance with electricity and heat storage.

4.4 Optimal retrofitting plan and its corresponding performance

The constitution of investment cost, life-time cost-saving, energy reduction and carbon reduction at three optimisation objectives (i.e. optimal life-time cost-saving, optimal life-time energy reduction and optimal life-time carbon reduction) are summarised in Figs. 13-15, respectively. The total life-time is set as 60 years. If the life-time of a particular retrofitting option is smaller than 60 years, the equivalent investment cost, embodied energy and embodied carbon would be used. For example, the life-time of the CHP system is 15 years; thus, its equivalent investment cost is set to be four times the initial investment cost. The retrofitting solution under different initial investment cost and optimisation objective is summarised in Table 9. Roof and wall insulation is selected as the primary option for building retrofitting, followed by CHP system, biomass boiler, wind turbine, PV panel and solar heater. It is because that the total electricity demand is higher than that of total heating demand, while the CHP system has a low electricity-to-heat ratio. There exists a slight difference in retrofitting solution under different optimisation objectives, mainly owing to the different characteristic unit return cost, energy and carbon of each retrofitting option (i.e. Tables 7 and 8).

In Figs (b)(c)(d) of 13-15, the dots in different shapes and colours represent the life-time performance resulted from the enumeration study using various design areas and design power of each retrofitting option. It is seen that the red line, obtained from PSO optimisation, results in the global optimal life-time decarbonisation performance. It is also seen that life-time investment cost, energy consumption and carbon emission increases with the increase of initial investment cost. The largest life-time cost-saving, energy reduction and carbon reduction is £3.8×10^6, 3.7×10^8 MJ and 2.5×10^7 kg, respectively. Compared to the building without retrofitting, there could be 39%, 55% and 59% reduction of life-cycle economy, energy and environment, respectively. It is also seen that the optimal life-time energy and carbon reduction does not necessarily mean the smallest life-time cost saving.

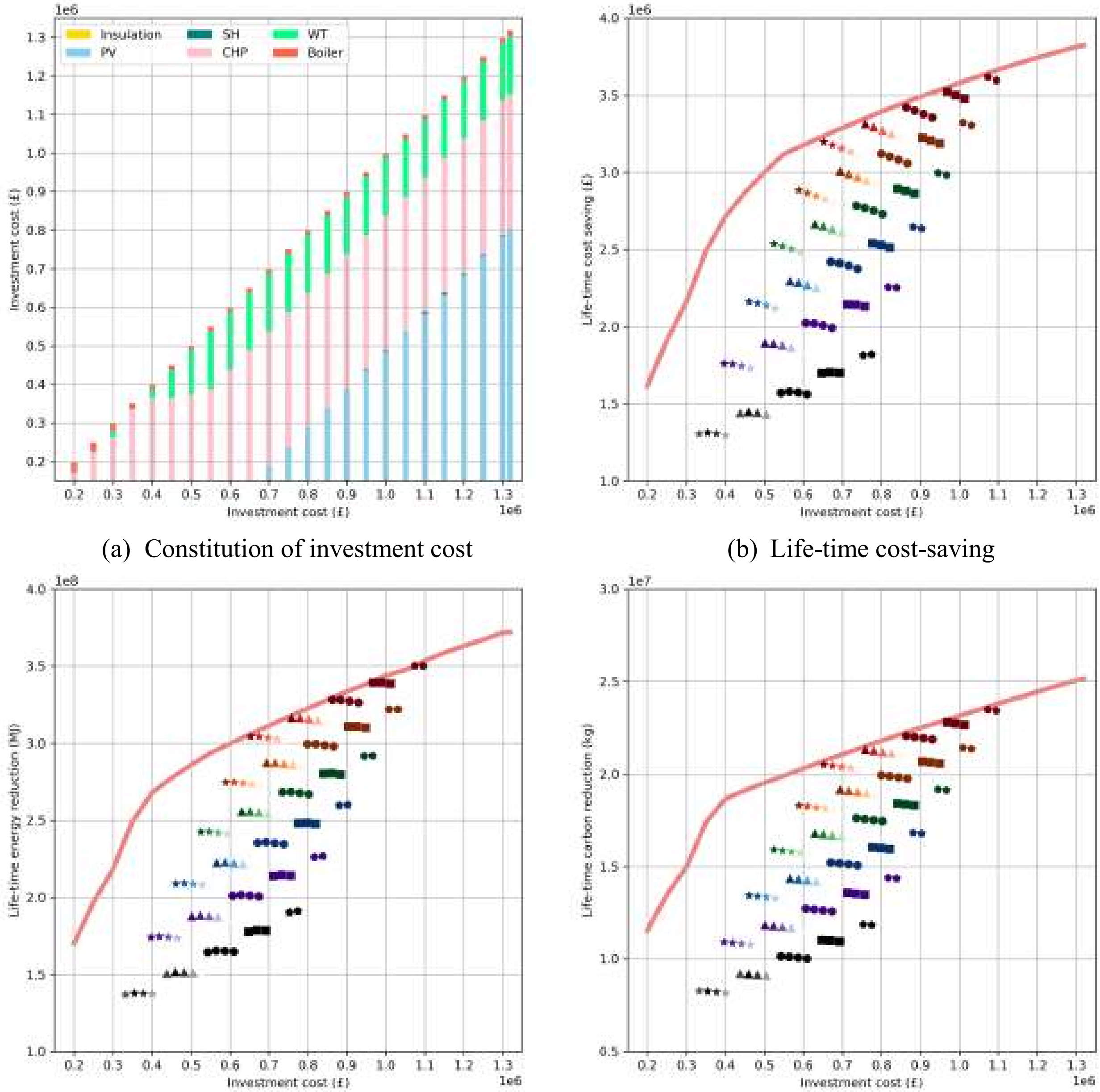
Please note that the investment cost of the entire insulation of the wall and roof is only £13850, so the yellow bar cannot be seen on Figs 12(a), 13(a) and 14(a). When the initial investment cost reaches its limit, roof and wall insulation results in the smallest investment cost, followed by the solar heater, biomass boiler, wind turbine, CHP system and PV panel.

At the largest possible investment cost (i.e. £1.32×10^6) of achieving optimal life-time cost-saving, the operating schedule of each energy device during winter and a summer day is summarised in Fig. 16.

Table 9. Summary of optimal retrofitting plan.

Investment cost (£)	Economic: Optimal life-time cost saving							Energy: Optimal life-time energy reduction							Environment: Optimal life-time carbon reduction						
	Wins (m^2)	Rins (m^2)	BB (kW)	PV (m^2)	SH (m^2)	CHP (kW)	WT (kW)	Wins (m^2)	Rins (m^2)	BB (kW)	PV (m^2)	SH (m^2)	CHP (kW)	WT (kW)	Wins (m^2)	Rins (m^2)	BB (kW)	PV (m^2)	SH (m^2)	CHP (kW)	WT (kW)
200000	585	1133	122	0	0	22	0	585	1133	122	0	0	22	0	585	1133	122	0	0	22	0
250000	585	1133	102	0	0	30	0	585	1133	102	0	0	30	0	585	1133	102	0	0	30	0
300000	585	1133	89	0	0	35	5	585	1133	82	0	0	38	0	585	1133	82	0	0	38	0
350000	585	1133	63	0	0	46	0	585	1133	77	0	0	40	12	585	1133	63	0	0	46	0
400000	585	1133	52	0	0	50	7	585	1133	52	0	0	50	7	585	1133	52	0	0	50	7
450000	585	1133	52	0	0	50	24	585	1133	52	0	0	50	24	585	1133	52	8	0	50	23
500000	585	1133	52	18	0	50	38	585	1133	52	0	0	50	41	585	1133	52	42	0	50	33
550000	585	1133	52	43	0	50	50	585	1133	52	43	0	50	50	585	1133	52	103	0	50	39
600000	585	1133	52	139	0	50	50	585	1133	52	138	0	50	50	585	1133	52	188	0	50	41
650000	585	1133	52	233	0	50	50	585	1133	52	321	0	50	35	585	1133	52	242	0	50	48
700000	585	1133	52	328	0	50	50	585	1133	52	328	0	50	50	585	1133	52	475	0	50	24
750000	585	1133	52	423	0	50	50	585	1133	52	468	0	50	42	585	1133	52	555	0	50	27
800000	585	1133	52	518	0	50	50	585	1133	52	518	0	50	50	585	1133	52	569	0	50	41
850000	585	1133	52	613	0	50	50	585	1133	52	613	0	50	50	585	1133	52	673	0	50	40
900000	585	1133	52	709	0	50	50	585	1133	52	772	0	50	39	585	1133	52	794	1	50	35
950000	585	1133	53	798	21	50	50	585	1133	50	842	33	50	42	585	1133	50	869	27	50	38
1000000	585	1133	50	893	30	50	50	585	1133	50	892	35	50	50	585	1133	50	989	27	50	33
1050000	585	1133	60	988	12	50	50	585	1133	50	1057	38	50	38	585	1133	50	1105	34	50	29
1100000	585	1133	51	1080	42	50	50	585	1133	47	1083	82	50	48	585	1133	54	1109	25	50	45
1150000	585	1133	19	1175	48	50	50	585	1133	49	1175	48	50	50	585	1133	54	1214	25	50	44
1200000	585	1133	53	1272	34	50	50	585	1133	49	1270	49	50	50	585	1133	55	1319	25	50	42
1250000	585	1133	57	1368	19	50	50	585	1133	49	1364	55	50	50	585	1133	56	1385	23	50	47
1300000	585	1133	56	1463	22	50	50	585	1133	55	1462	29	50	50	585	1133	60	1463	11	50	50
1320000	585	1133	66	1133	0	50	50	585	1133	66	1133	0	50	50	585	1133	66	1133	0	50	50

Wins: Wall insulation; Rins: Roof insulation; BB: Biomass boiler; PV: PV panel; SH: Solar heater; CHP: CHP system; WT: Wind turbine



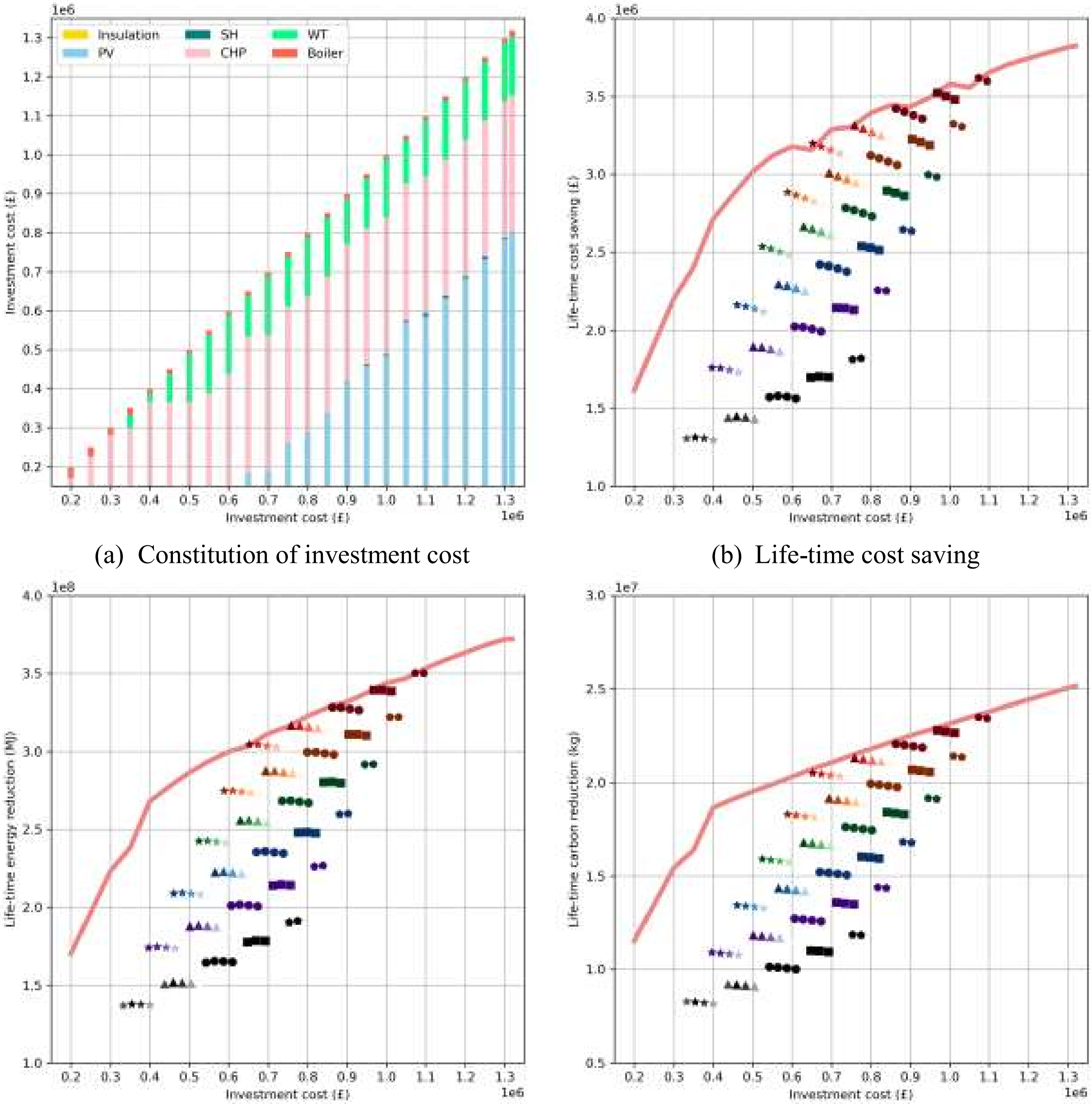
(a) Constitution of investment cost

(b) Life-time cost-saving

(c) Life-time energy reduction

(d) Life-time carbon reduction

Fig. 13. Investment cost distribution and life-cycle performance with the optimisation objective of life-time cost saving.



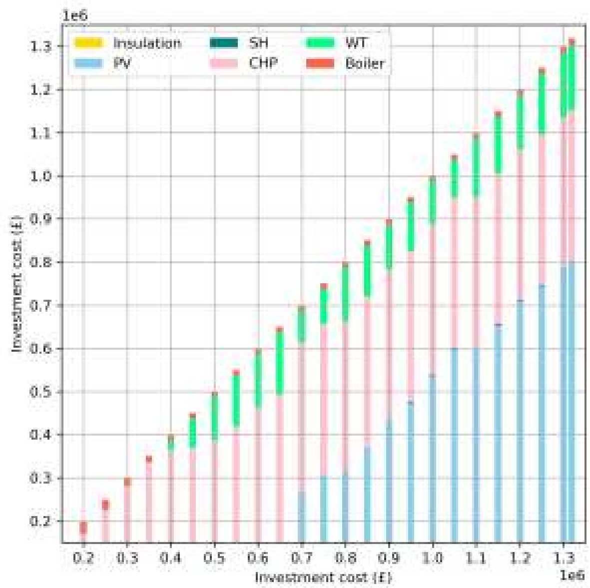
(a) Constitution of investment cost

(b) Life-time cost saving

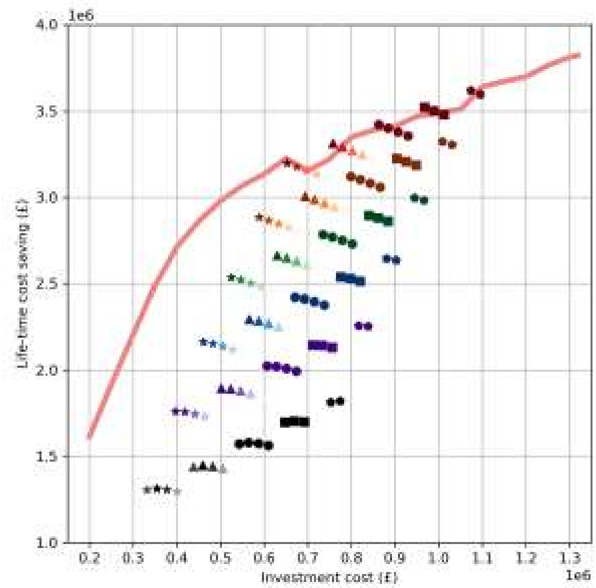
(c) Life-time energy reduction

(d) Life-time carbon reduction

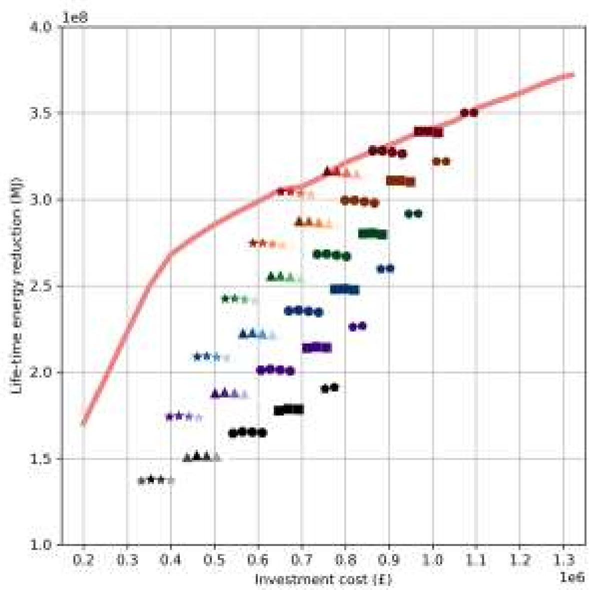
Fig. 14. Investment cost distribution and life-cycle performance with the optimisation objective of life-time energy reduction.



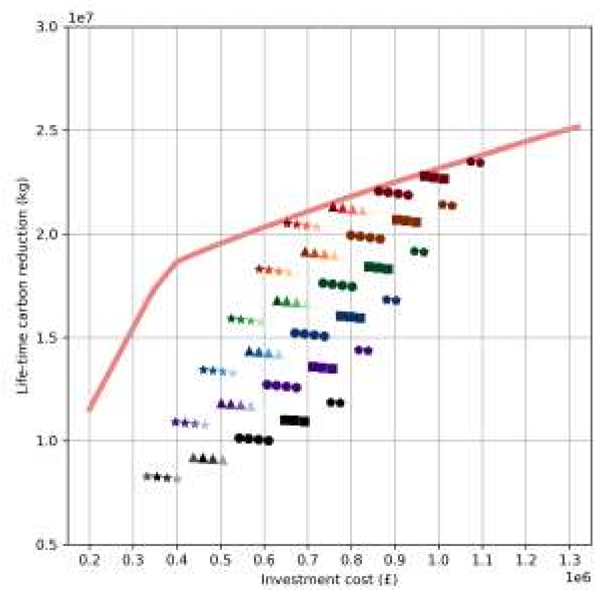
(a) Constitution of investment cost



(b) Life-time cost saving



(c) Life-time energy reduction

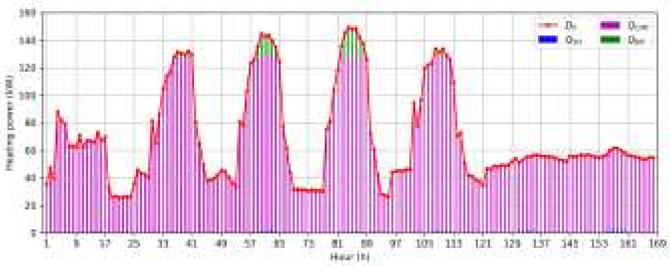


(d) Life-time carbon reduction

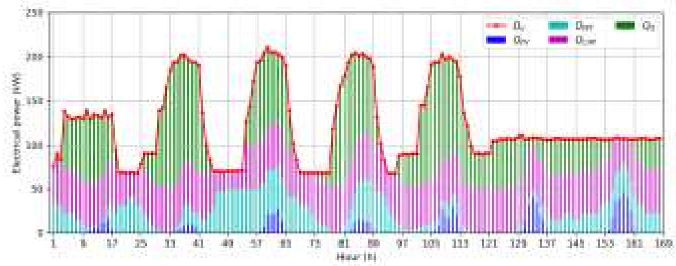
Fig. 15. Investment cost distribution and life-cycle performance with the optimisation objective of life-time carbon reduction.

- For heating supply, the actual thermal energy production from the solar heater is determined by the solar radiation and outdoor air dry-bulb temperature. It is relatively small in winter while relatively large in summer. The CHP system is the primary heating supplier, while the biomass boiler would be adopted if the heating energy from the CHP system is not sufficient.
- For electricity supply, the electrical power from PV panel and wind turbine is determined by the actual solar radiation, wind speed and outdoor air dry-bulb temperature, respectively. CHP system would be

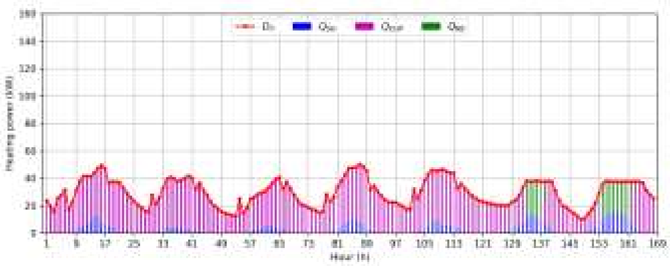
adopted to supplement the electricity supply. If it is still not sufficient, extra electricity would be imported from the power grid. It is also noticed that there exists extra electricity production from PV panel and wind turbine during weekends in summer. It is owing to the large solar radiation in summer while low electricity demand at weekends.



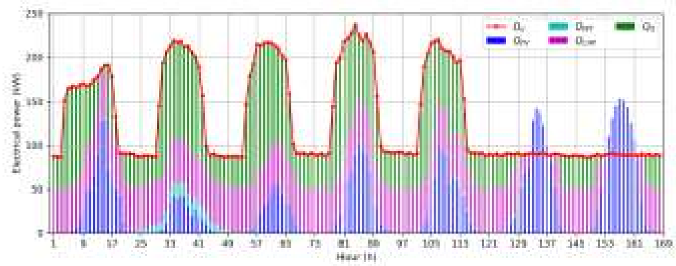
(a) Winter, heating



(b) Winter, electricity



(c) Summer, electricity



(d) Summer, electricity

Fig. 16. The operating capacity of each energy device for heating and electricity demand.

5. Practical implication and future study

In this study, the data-driven life-cycle optimisation approach is proposed for building retrofitting, while an existing office building in real life is adopted to test its performance. At the preparation stage, at least one year of historical energy consumption profile from the building management system, one year of historical weather data from the local weather station, building thermal properties from building information model, and inventory information of different retrofitting materials should be collected and served as big-data as input. After that, the economic, energetic and environmental decarbonisation and life-cycle performance of each retrofitting option can be evaluated. Through the proposed life-cycle optimisation approach, the optimal retrofitting plan for optimal life-time cost-saving, energy reduction and carbon reduction can be obtained. By implementing the optimal retrofitting plan on various office buildings, a large amount of energy consumption and carbon footprint can be reduced through its entire life-cycle. This could serve as a big step in preserving energy resources, mitigating climate change problems and realising net-zero ambition.

The principal purpose of this study is to propose the data-driven life-cycle optimisation approach for building retrofitting. Although this study only considers roof insulation, wall insulation, wind turbine, solar heater, biomass boiler, CHP system and PV panel as retrofitting options, other retrofitting materials such as floor insulation and window insulation can be easily included. Apart from operating cost, energy consumption and carbon emission, indoor air quality is also vital in improving building sustainability. Heating, ventilation and air conditioning system can be adopted to enhance indoor environmental quality on various fronts, such as thermal comfort and pollutants reduction (i.e. particulate matter, total suspended particulate, carbon monoxide, sulphur dioxide, nitrogen dioxide, and volatile organic compound). In this study, the entire office is regarded as a lump thermal model, while the indoor temperature is assumed to be homogenous. In future research, the computational fluid dynamic analysis could be conducted to investigate the optimal distribution of inlet and outlet air diffusers. Moreover, in this study, one year of historical weather profile and energy data is adopted for estimating the optimal retrofitting plan. The effects of climate change on the retrofitting design should be considered in the future study.

6. Conclusion

Conventional retrofitting optimisation approaches are generally devised with the aim of achieving the minimum operating energy or cost. However, the increase in embodied energy and carbon is not considered. It is vital to consider the energy consumption and carbon emission from its entire life cycle in an effort to achieve climate-neutral by 2050. In this study, a novel data-driven life-cycle optimisation approach is proposed for building retrofitting, along with a comprehensive assessment of the economy, energy and environment performance. There exist three levels of innovation of the proposed optimisation approach.

- First of all, accurate real-life building performance evaluation is achieved through modelling using big-data information. The big-data information includes historical energy consumption profile from the building energy management system, actual building thermal property from the building information system, historical weather data from the local weather station, as well as real-world life-cycle inventory information.
- Secondly, enhanced energy performance is achieved through integrated retrofitting design. The various retrofitting measures include wall insulation and roof insulation for decreasing thermal energy demand, solar heater and PV panel for utilising solar energy, as well as biomass-fuelled CHP system and biomass boiler for using biomass energy. The coordination among these retrofitting options for satisfying building heating and electrical energy demand can reach accumulative effects for enhanced energy performance.

- Life-cycle energy and carbon reduction maximisation is obtained through life-cycle optimisation on economy, energy and environment. The embodied energy and carbon of raw material extraction and manufacturing, as well as the released energy and carbon during the end-of-life recycling stage, is considered. The optimal retrofitting plan can maximise life-time cost-saving, life-time energy reduction and life-time carbon reduction.

The proposed retrofitting optimisation approach is implemented on a pre-existing three-floor office building in the United Kingdom to test its performance. The optimal retrofitting plan can provide valuable insights into building life-cycle performance for facility managers to take high-performance retrofitting measures and to help mitigate climate change problems. The valuable information from this case study is summarised as follows.

- Wall and roof insulation has the smallest unit return cost (i.e. 0.061£/£), unit return energy (i.e. 0.445£/GJ), unit return carbon (i.e. 0.009£/kg), followed by the solar heater, CHP system, biomass boiler, wind turbine and PV panel.
- Life-time cost-saving, energy reduction and carbon reduction increases with the increase of its design power of biomass boiler, CHP system and wind turbine, as well as design area of wall insulation, roof insulation, PV panel and solar heater.
- The unit return cost, energy and carbon are relatively constant when the design power of the wind turbine is smaller than 50 kW, the design area of the solar heater is smaller than 20 m^2, the design power of the CHP system is smaller than 25 kW, and the design area of PV panel is smaller than 500 m^2. When the design power and design area of the corresponding retrofitting energy device are larger than those values, the unit return cost, energy and carbon would increase with the increase of those design power and design area.
- For wind turbine and PV panel, the life-time cost-saving decreases with the increased capacity of electricity storage. It indicates that the investment cost of electricity storage itself cannot be made up by its shifting ability for renewable energy production and building electrical energy demand. For the solar heater, the life-time cost-saving and energy reduction increases with the increased capacity of heat storage. However, the life-time carbon reduction decreases with the increased capacity of heat storage.
- Through the proposed retrofitting optimisation approach, roof and wall insulation are selected as the primary option for building retrofitting, followed by CHP system, biomass boiler, wind turbine, PV panel and solar heater. The largest life-time cost-saving, energy reduction and carbon reduction is £3.8×10^6, 3.7×10^8 MJ and 2.5×10^7 kg, respectively, at the investment cost of £1.32×10^6.

It is expected that similar sets of conclusion can be reached by applying the proposed retrofitting optimisation approach to other office buildings. Thus, it can provide building engineers and facility managers with in-depth and valuable guidelines for building retrofitting. As a result, the building can be retrofitted towards the life-cycle economic, energetic and environmental optimum to achieve life-cycle net-zero ambitions.

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Nomenclature

A	Surface area
$CLTD$	Cooling load temperature differences
c	Random values
e	Unit economic cost, energy consumption or carbon emission
G	Global solar radiation
$gbest$	Global best value
LS	Life span
P	Unit return
$pbest$	Particle's best value
Q	Energy generation or consumption rate
R	Recycle ratio
r	Charging or discharging rate
T	Temperature
U	Heat transfer coefficient
V	Velocity of PSO algorithm
X	Decision variable (i.e. design area or design power)
γ	Parameters of PSO
η	Efficiency
ε	Correction coefficient

Subscripts

bio	Biomass
BB	Biomass boiler
CE	Carbon emission
ch	Charging rate
CHP	Combined heat and power system
CO	Economic cost
DB	Dry-bulb
dch	Discharging rate
e	Electrical
ele	Electricity consumption
EN	Energy consumption
ES	Electricity storage
GB	Gas boiler
h	Heating
HS	Heat storage
ng	Natural gas
PG	Power grid
PV	PV panel
ref	Reference
RI	Roof insulation
SH	Solar heater
trans	Transmission
WI	Wall insulation
WT	Wind turbine

Superscript

emb	Embodied
inv	Investment
pre	Pre-retrofitting
post	Post-retrofitting
rec	Recycle

Abbreviations

CHP Combined heat and power

PSO Particle swarm optimisation

PV Photovoltaic

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