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An integrated passive and active retrofitting approach toward minimum whole-life carbon footprint

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ABSTRACT

The state-of-the-art retrofitting strategies generally use either passive or active measures to reduce carbon emissions during its operating stage. The coordination among a range of passive and active energy devices is not considered while the concept of whole-life carbon emission minimisation is not introduced. To overcome these three research gaps and to transform existing office buildings toward minimum whole-life carbon emissions, an integrated passive and active retrofitting approach is proposed. Through two inter-related design optimisation and operating optimisation processes, the set of retrofitting options can be identified to achieve overall optimal economic, energy, and environmental performance. The first research gap, lack of simultaneous consideration of various active and passive retrofitting measures, is solved by the whole system simulation of a range of active and passive refurbishment measures. The second research gap, lack of coordination among a range of active energy devices, is solved by iteratively determining the optimal operating schedules of active energy devices with overall retrofitting plan at the design stage. The third research gap, lack of whole-life carbon emission minimisation, is solved by simultaneously minimising both embodied and operating carbon emissions. A real three-floor office building acquiring retrofitting is used to test the effectiveness of this integrated passive and active retrofitting approach. Compared to the building at its current status, there could be 44%, 74% and 68% reduction in lifelong costs, carbon emissions and energy usages if the proposed retrofitting strategy is adopted. Compared to retrofitting the building using the state-of-the-art "design optimisation only" strategy, the proposed retrofitting approach can reduce 5.36%-34.37% whole-life energy consumption and 4.31%-51.10% carbon emissions. Compared to retrofitting the building using the state-of-the-art "operating carbon emission only" strategy, there is 11.92%, 10.55%, and 10.48% reduction in whole-life cost, energy usage and carbon emissions, respectively. Therefore, this paper is innovative in an aspect that minimum whole-life carbon emissions can be reached through integrated design of passive and active retrofitting measures. It can provide building owners, energy engineers and decision-makers with insightful building retrofitting solutions to tackle the energy crisis and climate change problems. This proposed retrofitting approach can also be modified to provide guidance in designing new low-carbon buildings.

1. Background and research aim

Carbon emission from fossil fuels is the major contributor to global warming [1]. Various methods and technologies have been proposed to reduce carbon emissions caused by mining and burning fossil fuels. For example, a full understanding of closing-to-wall air has been proposed to reduce the corrosive area and carbon emissions from pulverized-coal furnaces and boilers [2]. The base and part load operation of natural gas combined cycle power plant integrated with post-combustion carbon capture plant and selective exhaust gas recirculation scheme have been proposed to reduce the size of capture plant and reboiler duty [3]. A novel technology, combining microwave irradiation with NaOH-H2O2, has been proposed to remove organic sulphur from coal [4]. Response surface methodology and artificial neural network models have been developed for enhancing lignin from industrial crops [5]. The strength degradation mechanism of iron coke has been investigated to develop a new type of blast furnace burden and facilitate green production of iron making [6]. Various Eulerian–Eulerian models have been developed to study the mixing and separation of multi-component particles in fluidized beds [7].

Despite of these technology developments for fossil fuels, buildings

Abbreviations: PSO, Particle swarm optimisation; SH, Solar heating system.

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Nomenclature

C	Quantity
D	Design area or capacity (m^2 or kW)
e	Energy stored in the electricity storage (kWh)
E	Energy demand (kW)
O	Operating capacity (kW)
r	Ratio
S	Pre-set area or capacity (m^2 or kW)
α	Carbon factor
η	Efficiency
Subscripts	*Retrofitting option*
BB	Biomass boiler
CHP	Biomass cogeneration system
ES	Electricity storage
RI	Roof insulating material
SH	Solar water heating system
WI	Wall insulating materials
WT	Wind generator
Status	
ch	Charging
dch	Discharging
emb	Embodied
ope	Operating stage
pre	Pre-retrofitting
rec	Recycling stage
LS	Life span
Resources	
bio	Biomass
e	Electricity
h	Heat
Indicators	
ca	Carbon emission
co	Cost
en	Energy usage
Superscripts	
t	Time step

sector remains a major sector in carbon emissions, and it emitted 40% of the global carbon dioxide in 2019 [8]. The carbon emissions are anticipated to increase 0.1–0.3% each year until 2050 [9]. The construction, architecture, and engineering industry should work together to diminish carbon emissions by retrofitting a large number of existing buildings. Passive retrofitting measures, such as insulation materials, solar heating systems, solar panels, and wind generators, are weather-induced and do not require occupancy control. They are generally adopted to reduce heat loss (i.e., insulation materials) or convert renewable energy into useful electrical energy (i.e., solar panels and wind generators) and thermal energy (i.e., solar heating system), while the potential of carbon reduction of these retrofitting measures is determined by the initial retrofitting plan and meteorological conditions [10]. On the contrary, active retrofitting measures, such as biomass-fuelled combined heat and power (CHP) systems and biomass-fuelled boilers, are operator-induced. They generally require human intervention and can generate heat and electricity at a high efficiency by consuming primary energy [11]. The carbon reduction ability of active retrofitting measures is determined by the actual operating schedules. Therefore, it is important to consider the integrated design of both passive and active retrofitting measures. The primary aim of this piece of work is to develop an integrated passive and active approach to retrofitting office buildings toward minimum whole-life carbon emissions. Passive measures include envelope insulations to decrease heat load during cold seasons; solar panels and wind generators to increase on-site electricity supply; as well as solar heating systems to increase on-site heat supply. Meanwhile, active measures consist of CHP systems and biomass boilers to boost thermal and electrical energy utilisation. As the design parameters of one retrofitting measure may affect the optimal design parameters of other retrofitting measures, the optimal coordination among a range of retrofitting measures is achieved through the iterative design optimisation and operating optimisation.

2. Literature review

2.1. Overview of up-to-date building retrofitting approaches

There are three types of up-to-date building refurbishment approaches. The first type demonstrates that both passive and active retrofitting measures can reduce year-round operating costs and energy use of buildings. State-of-the-art passive retrofitting measures mainly consist of envelope insulation [12–19], window replacement [16–21], shading system [18,19], photovoltaic (PV) panel [13,17,21], solar heating systems [17], cork as insulators [22,23] and phase change materials on building envelope [24,25]. The active retrofitting measures mentioned in previous studies mainly include lighting [19,26], air conditioning systems [22] and forced ventilation [27]. Passive and active retrofitting measures were investigated separately by different researchers. Design parameters, such as type, area and number of each retrofitting measure, were optimised to obtain the optimal combination of retrofitting options. Genetic algorithm (GA) [15,16,18,19,21], linear heuristic optimisation [20], and differential evolution [26] were proved effective at selecting discrete and continuous retrofitting design variables. In these studies, building energy performance was mainly estimated by first-principal equations and degree days [14,15,21] or thermodynamic models [12,16,18–20] using EnergyPlus software. For those active retrofitting measures, such as lighting and air condition systems, they were mainly operating at constant load while the purpose was to improve rated efficiency by system replacement. Liu et al. [28] developed an approach to designing building layouts and associated energy systems using building information modelling. Design optimisation was conducted in terms of adjacent built environment, heat loss performance, and energy conservation improvement.

The second type of research work demonstrates that the whole-life economy, energy, and environmental performance of retrofitted buildings can be evaluated according to different operating strategies. Life-cycle economic impacts are mainly dependent on the initial investing costs of retrofitting materials, along with maintenance costs and operating costs when the buildings are retrofitted. Life-cycle energy and environmental impacts are determined by primary energy usage at production, operating and disposal stages. The investigated retrofitting measures included envelope insulation [29–34], window replacement [31], solar energy conversion system [35], boiler replacement [31], lighting system [31], heating and cooling system replacement [29,32], district heating system [34], and CHP system [34], etc. In these previous research works, life-cycle economy, energy and environmental performance evaluation was conducted on individual adoption of each retrofitting measure, while the constant load was assumed for those active energy devices. Energy behaviour of the building was simulated by thermodynamic models using various energy simulation software, such as VIP [29], SimaPro [30], HOT2000 [31], ENSYST [34] and TRNSYS [35].

The third type of research works demonstrates that life-cycle cost can be optimised through various optimisation algorithms, such as genetic algorithm (GA) optimisation [36–38] and mixed-integer linear programming [39–41]. Life-cycle cost is the total of capital costs, operating costs and maintenance costs. The operating costs consist of energy costs for fuel consumption and electricity bought from the grid [36]. The majority of this type of studies focused on passive retrofitting measures such as roof insulating material [40–43], wall insulating material [39–42], solar panel [36,40], solar collectors [39,41], glazing and shading systems [37,42], ground source heat pump [36], and phase-change material enhanced opaque envelope [38]. Only a few of them considered the active retrofitting measures. For example, Jafari *et al.* [36] and Mejjaouli *et al.* [41] assessed the whole-life economy performance of replacing existing lighting, heating and cooling systems, and electrical equipment with highly efficient ones. Zheng *et al.* [40] investigated the effect of rated capacity of CHP system on its life-cycle cost. The rated capacity of the CHP system was chosen at the design stage, while it was assumed to constantly operate at full load during the actual operating stage. Rabani *et al.* [42] explored the relationship between lifelong cost of the air conditioning system and its supply air temperature. The supply air temperature was chosen at the retrofitting stage while it would not change during the actual operating stage.

In the author's previous research works, a retrofitting design approach was developed to choose the best possible set of passive measures and achieve minimum lifelong greenhouse gas emissions, primary energy use, and economic costs, respectively [44]. Another retrofitting design approach was proposed to choose the best possible set of passive measures to simultaneously achieve whole-life carbon–neutral and maximum lifetime payback cost [45]. However, these two retrofitting design approaches were purely based on passive refurbishment methods (i.e., envelope upgradation and renewable energy devices), whose operating schedules are weather induced. Another retrofitting design approach was developed to integrate supply-side management and life-cycle optimisation [46]. However, only one active energy device (i.e., cogeneration system) was considered to achieve minimum energy usage. To consider the influence of climate change on future changes in weather condition and energy usage, a retrofitting design approach was developed to minimise whole life costs and select optimal combination of refurbishment solutions for commercial buildings [47]. Additionally, an optimisation algorithm was developed to select the most appropriate retrofitting solutions and maximise the reduction in lifelong greenhouse gas emissions, primary energy use, and economic costs [48]. However, active energy devices in these two studies [47,48] were assumed to operate following thermal or electric load. In these studies, actual building energy consumption was adopted to validate the developed TRNSYS simulation models.

2.2. Research gaps

A summary of literature review is presented in Table 1, in terms of energy simulation model, retrofitting options, retrofitting objectives, optimisation approaches, whether life-cycle optimisation was considered, and whether operating optimisation was considered in each of the previous research works. The purpose of Table 1 is to summarise the state-of-the-art research works in different aspects so as to identify significant research gaps. The above literature review indicates that appropriate retrofitting approaches can successfully decrease carbon emissions, energy usage, and operating costs. However, there still exists three significant research gaps:

- <u>Collective performance of various active and passive retrofitting measures is not considered</u>

The effects of individual adoption of passive measures (e.g., envelope insulating materials [12–21,29–34,36–45,47,48], triple-glazed window [12,16,19,21,39,42,44,47,48], shading system [18,19,37], solar panel [13,21,31,36,40,44–48] and solar heating system [14,17,35,36,39,41,44–48]) were evaluated separately in most previous research works. Meanwhile, other researchers investigated energy-saving performance through individual adoption of active retrofitting measures such as the replacement of energy-efficient lighting [17,31], heating [29,31,32,34], and cooling systems [32,41,42]. However, there is a lack of study evaluating the collective effects of multiple active and passive retrofitting measures. In fact, if envelope insulation is adopted, the heat demand of the building will be decreased, which might result in the reduced design capacity of solar boiler. Therefore, the optimal design parameters of both active and passive retrofitting measures should be considered at the same time.

- <u>Lack of whole-life carbon footprint evaluation</u>

Most previous research works considered economic and energy effects. For example, they set either year-round cost [14,20,30,31], year-round energy consumption [12–15,17,18,21,26], life-cycle energy consumption [12–15,29–31,34,35,44], life-cycle cost [16,17,19,21,26,36–44], thermal comfort [15,17,18] or embodied energy and carbon [32,33] as primary retrofitting criteria. Although few studies mentioned carbon emissions [16,19,39], only the operating carbon emissions were minimised. In fact, there exists a certain amount of carbon emissions from retrofitting materials during their production phase, which is called embodied carbon. If the embodied carbon of retrofitting materials is high, even when year-round carbon emissions are reduced, the overall whole-life carbon emissions might even be higher.

- <u>Lack of a circular iterative process of design and operating optimisation</u>

For passive retrofitting options, the annual reduction in energy consumption and production from renewable energy devices are entirely dependent on meteorological factors once the design capacity is determined. On the other hand, the improvement of energy performance through active retrofitting options is determined by human intervention. The optimal operating schedules of active retrofitting devices, along with proper retrofitting plan, will result in more distinct energy reductions. Although replacement of lighting [17,31] and air conditioning system [41,42] was considered in some of the previous works, the primary measure was to improve the rated efficiency of the equipment itself. These active energy devices were operated at constant capacity or using conventional following electric load strategy. Therefore, the proper coordination among different active and passive energy devices was not considered to achieve an overall optimal operating efficiency.

2.3. Contribution

Because of the above three knowledge gaps, this research aims at proposing an integrated passive and active approach to retrofit office buildings toward whole-life minimum carbon emissions. The proposed retrofitting approach will have the following three featuring attributes:

- <u>An optimal combination of multiple active and passive measures</u>

To overcome the research gap of lack of collective performance evaluation of both active and passive retrofitting measures, a whole system simulation model is developed in this study to investigate the optimal combination of multiple active and passive measures. Passive measures include envelope insulations to decrease heat load during cold seasons; solar panels and wind generators to increase on-site electricity supply; as well as solar heating systems to increase on-site heat supply. Meanwhile, the effects of the CHP system and biomass boiler in boosting thermal and electrical energy utilisation are also explored. These retrofitting measures (i.e., envelope insulations [12–21,29–34,36–45,47,48], solar panels [13,21,31,36,40,44–48], wind generators [44,47,48], solar heating system [14,17,35,36,39,41,44–48], CHP system [47,48], and biomass boiler [46–48]) have been widely tested in previous works and demonstrated to be useful in practical building

Table 1
Summary of state-of-the-art research works on building retrofitting strategies.

Ref	Energy simulation model	Retrofitting options Passive	Active	Retrofitting objectives	Optimisation approach	Is life-cycle optimisation considered?	Is operating optimisation considered?
12	Thermodynamic model (EnergyPlus software)	Envelope insulation, window type and design	N.A.	Year-round energy reduction	Orthogonal Array Testing	No	No (all passive retrofitting options)
13	IES-VE energy simulation software	Envelope insulation and PV system	N.A.	Year-round energy reduction	Performance evaluation	No	No (all passive retrofitting options)
14	First-principal equations & degree days	Type of window, wall, roof insulating material, and solar heating system	N.A.	Retrofitting cost and year-round energy reduction	Tchebycheff programming	No	No (all passive retrofitting options)
15	First-principal equations & degree days	External wall and roof insulating material	N.A.	Year-round energy reduction, thermal comfort	GA	No	No (all passive retrofitting options)
16	Thermodynamic model (EnergyPlus software)	Glazing system and envelope insulation	N.A.	Investment cost, year-round energy cost and carbon emissions	GA	No	No (all passive retrofitting options)
17	SimBldPy modeling tool and random forest models	Window replacement, wall and roof insulating material, air tightness, solar panels and solar heating system	HVAC operation, lighting	Year-round energy reduction, cost saving, thermal comfort and investment cost	Different combinations	Multi-objective on investment and operating cost	No (fixed operation of HVAC system)
18	Thermodynamic model (EnergyPlus software)	Building envelope, shading system and window replacement	N.A.	Year-round energy consumption and thermal comfort	NSGA-II optimisation algorithm	No	No (all passive retrofitting options)
19	Thermodynamic model (EnergyPlus software)	Envelope insulation, window, shading and lighting system	N.A.	Investment cost, year-round carbon emissions	GA	No	No (all passive retrofitting options)
20	Ensemble calibration	Wall insulating material, roof insulating material and glazing design	N.A.	operating cost during a period	linear heuristic optimisation	No	No (all passive retrofitting options)
21	First-principal equations & degree days	Types of windows, external walls, roof insulating materials type, and area of solar panel	N.A.	Energy saving, net present value and payback time	GA	No	No (all passive retrofitting options)
26	Empirical coefficient	N.A.	Lights, pumps, chillers and heaters	Year-round energy saving, net present value and payback time	Differential evolution	No	No (all retrofitting options work on constant load)
29	Thermodynamic model (VIP simulation software)	Upgraded insulation	Different heating systems	Life-cycle energy consumption	Performance evaluation	Energy evaluation	No (all passive retrofitting options)
30	Thermodynamic model (SimaPro v9.0 software)	Insulating materials, cladding system, and thermal-insulating windows	N.A.	Life-cycle energy, economy and environment	Performance evaluation	3E evaluation	No (all passive retrofitting options)
31	Thermodynamic model (HOT2000 energy simulation software package)	Envelope insulation and solar panel	Replacement of LED lighting, and boiler with higher efficiency	Life-cycle cost, life-cycle energy	Performance evaluation	No	No (all passive retrofitting options or at fixed schedule)
32	Empirical coefficient (Athena Impact Estimator for Buildings 5.2)	Envelope insulation	Replacement of heating and cooling system	Embodied energy and carbon	Performance evaluation	No	No (all passive retrofitting options or at fixed schedule)
33	Thermodynamic model (AccuRate's simulation engine)	Envelope insulation	N.A.	Embodied energy and carbon	Performance evaluation	No	No (all passive retrofitting options)
34	Thermodynamic model (ENSYST software)	Roof, windows and wall insulating material	District heating system and CHP system	Life-cycle energy	Performance evaluation	Energy evaluation	No (active system works at base load)
35	Thermodynamic model (TRNSYS software)	Solar heating system	Electricity system	Life-cycle energy and environment impacts	Performance evaluation	Energy and environment evaluation	No (all passive retrofitting options)
36	Thermodynamic model (eQuest simulation software)	Envelope insulation, GHSP, solar heating system, solar panel.	HVAC operation, equipment operation	Investment cost and future cost	GA	Investment and operating cost as 2 objectives	No (all passive retrofitting options)
37	Thermodynamic model (EnergyPlus software)	Wall insulating material, roof insulating material, exterior shading and glazing design	N.A.	Life-cycle cost	GA	Cost optimisation	No (all passive retrofitting options)
38	Thermodynamic model (EnergyPlus software)	PCM-enhanced opaque building envelope	N.A.	Life-cycle cost	NSGA-II optimisation	Cost optimisation	No (all passive retrofitting options)
39	Mathematical thermodynamic model	Types of windows and walls, roof insulating materials, and solar heating systems	N.A.	Life-cycle costs and year-round greenhouse gas emissions	MILP	Cost optimisation	No (all passive retrofitting options)

(*continued on next page*)

Table 1 (*continued*)

Ref	Energy simulation model	Retrofitting options Passive	Active	Retrofitting objectives	Optimisation approach	Is life-cycle optimisation considered?	Is operating optimisation considered?
40	Mathematical thermodynamic model	Envelope insulation, solar panel	CHP system	Life-cycle cost	MINLP model and Lindo optimiser	Cost optimisation	No (CHP works at constant load)
41	Mathematical thermodynamic model	Roof and wall insulating material and solar heating system	Replacement of air conditioner, lights & electrical equipment	Life-cycle cost	Mixed Integer Linear Programming	Cost optimisation	No (all passive retrofitting options or at fixed schedule)
42	Thermodynamic model (IDA-ICE)	Window type; Wall, floor, and roof insulating materials; external shading	HVAC operation	Life-cycle cost	Graphical script	Cost optimisation	No (fixed operation of HVAC system)
43	Thermodynamic model (EnergyPlus software)	Roof insulating material	N.A.	Life-cycle cost	multi-criteria ordinal classification	Cost optimisation	No (all passive retrofitting options)
44	Thermodynamic model (TRNSYS) validated with case study buildings	Wall/roof insulating material, triple-glazing window, solar panel, solar heating system and wind generator	N.A.	Life-cycle cost, carbon emission and energy use	Enumeration optimisation	Cost, carbon emission and energy use, respectively	No (all passive retrofitting options)
45	Thermodynamic model (TRNSYS) validated with case study buildings	Envelope insulating materials, solar panel, solar heating system and wind generator	Biomass trigeneration system and biomass boiler	Life-cycle carbon emissions	Manual comparison	Yes, lifetime payback cost	No (all passive retrofitting options)
46	Thermodynamic model (TRNSYS) validated with case study buildings	Solar panel, solar heating system and biomass boiler	Heat pump, energy storages, and cogeneration system	Life-cycle energy consumption	Ant colony optimisation	Yes, life cycle energy	Yes, but only one active energy device
47	Thermodynamic model (TRNSYS) validated with case study buildings	Wall/roof/floor insulating materials, triple-glazing window, solar panel, solar heating system and wind generator	Biomass trigeneration system and biomass boiler	Life-cycle cost	PSO	Yes, cost optimisation	No, conventional following electric/ thermal load strategy is adopted
48	Thermodynamic model (TRNSYS) validated with case study buildings	Wall/roof/floor insulating materials, triple-glazing window, solar panel, solar heating system and wind generator	Biomass trigeneration system and biomass boiler	Life-cycle cost	PSO	Yes, cost optimisation	No, conventional following electric/ thermal load strategy is adopted

retrofitting. As the design parameters of one retrofitting measure may affect the optimal design parameters of other retrofitting measures, the optimal set of design parameters of different retrofitting options will be figured out using PSO optimisation.

- Whole-life minimisation of carbon emissions

To overcome the research gap of lack of whole-life carbon footprint, the whole-life minimisation is conducted. Whole-life carbon emissions refers to the gate-to-grave stage of the implemented retrofitting measures. Therefore, the total amount of embodied carbon during the retrofitting material production phase, operating carbon emissions during the building operating phase and the recycled carbon after the materials' end-of-life phase will be minimised based on the actual life cycle inventory information of each retrofitting measure.

- A circular iterative process of retrofitting plan and operating schedules optimisation

To overcome the research gap of lack of iterative optimisation of design and operating parameters, the retrofitting plan and operating schedules of active energy devices are determined through a circular iterative process. On the basis of varying energy demands and renewable energy production rates, the optimal operating schedules of biomass cogeneration system, electricity storage and biomass boiler are determined under each retrofitting plan. More importantly, the greenhouse gas emissions estimated at operating schedules optimisation formulates part of the overall objectives at the retrofitting plan optimisation stage.

3. Integrated passive and active retrofitting approach

This research work aims at developing an integrated passive and active retrofitting approach to explore optimal retrofitting plans and minimise while-life carbon emissions. Owing to year-round variation in energy demand and production, optimal operating schedules are critical to guarantee optimal carbon reduction performance from the biomass boiler and CHP system. Moreover, retrofitting plan design is influenced by active energy devices' operating schedules.

The inventory data of retrofitting materials is adopted to determine the embodied carbon at material production stage and recyclable carbon at the end-of-life stage. This information will be used in the first-set optimisation. The design information of the existing building is adopted to develop thermodynamic models of building physics, while historical meteorological and energy profiles are used to validate the developed thermodynamic models. The validated thermodynamic models of building physics, along with thermodynamic models of retrofitting measures and future weather profiles are used in the second-set optimisation. In the proposed integrated passive and active retrofitting approach, a circular iterative process of design and operating optimisation is utilised. The first-set optimisation and second-set optimisation determines retrofitting plan design and energy system optimal operating schedules, respectively. To be more specific, the first-set optimisation will determine the optimal retrofitting plan, which will be used as optimisation constraints for the second-set optimisation. Meanwhile, operating carbon emissions estimated by the second-set optimisation serve as continuous feedback to first-set optimisation, which formulates as part of the objective function. Therefore, these two sets of optimisation algorithms follow circular iterative processes. The flowchart of these circular two iterative processes is illustrated in Fig. 1.

3.1. First-set optimisation (Design optimisation)

The first-set optimisation aims at choosing the most appropriate retrofitting plan on the basis of the optimal operating carbon emissions from the second-set optimisation. It is assumed that the existing energy systems within the building will be fully replaced by the new retrofitting measures.

3.1.1. Design variables

The retrofitting plan include design areas of the roof insulating material D_{RI}, wall insulating material D_{WI}, solar panel D_{PV} and solar heating system D_{SH}; along with the design capacities of wind generator D_{WT}, biomass-fueled cogeneration system D_{CHP}, electricity storage D_{ES} and biomass boiler D_{BB}. Even though roof insulating material, wall insulating material, solar panel, solar heating system, wind generator, biomass-fueled cogeneration system, electricity storage and biomass boiler are assumed to be useful in existing building retrofitting, its design capacity or area may become 0 if it does not help reduce whole-life carbon emissions of the retrofitted building. In other words, the purpose of the first-set optimization is to determine whether each retrofitting measures will be utilised, and how much it will be utilised.

3.1.2. Objective function

First-set optimisation aims at minimising whole-life carbon emissions $C_{L,ca}$ of the retrofitted building. Whole-life carbon emissions refers to the gate-to-grave stage of the implemented retrofitting measures, which includes its embodied carbon at the production phase $C_{emb,ca,i}$, operating carbon emissions during its life span $\sum_{LS} C_{ope,ca,i}$, and recyclable carbon at its end of the life $C_{rec,ca,i}$ [44,45]. Since the life span of different retrofitting measures are varied, the retrofitting measures with the longest life span is used as a benchmark. A new replacement is assumed to be made for the retrofitting measures if its life span is shorter. For example, insulation materials have the longest life span (i.e., 60 years) and biomass CHP system has the shortest life span (i.e., 15 years) [47], thus, the carbon emissions from biomass CHP system will be quadrupled to get the equivalent whole-life carbon emission. The whole-life carbon emissions do not include the buildings carbon emission prior to its retrofitting. Therefore, Eq. (1) is used to estimate the whole-life carbon emissions from different retrofitting measures.

$$\min C_{L,ca} = \sum_{N} (C_{emb,ca,i} LS_s / LS_i + \sum_{LS_s} C_{ope,ca,i} - C_{rec,ca,i} LS_s / LS_i) \quad (1)$$

Here, i refers to different retrofitting measures, LS_s is the standard life span, which is 60 years in this study (equal to the life span of insulation materials), $C_{ope,ca}$ is the yearly operating carbon emissions and is the continuous feedback from second-set optimisation.

3.1.3. Optimisation constraints

D_{RI} and D_{WI} cannot exceed the roof area S_{roof} and external wall area S_{wall}. D_{PV} and D_{SH} should not be larger than the allowable design area S_{ren} set by the building owners. D_{WT}, D_{BB}, D_{CHP} and D_{ES} should not exceed the corresponding maximum desirable capacities of wind generator S_{WT}, biomass boiler S_{BB}, biomass CHP system S_{CHP} and electricity storage S_{ES} set by the building owners and facility managers.

3.2. Second-set optimisation (operating optimisation)

During the operating optimisation stage, the historical year-round weather condition is used to estimate the energy performance of each energy device, while nominal thermal or electrical efficiency is assumed for each energy device. Second-set optimisation aims at determining the appropriate operating schedules for each active energy device and achieving the minimum operating carbon emissions. Relying on the energy scheduling capability of electricity storage, renewable energy generated from solar panels, wind generators and solar heating systems can be extensively utilised by charging the electricity storage while there exists extra energy, whilst being discharged when renewable energy production is not sufficient. Therefore, the electricity storage can schedule the daily and weekly electricity load so as to solve the mismatch between renewable electricity production and building energy demands. It is also expected that the CHP system can be used as much as possible owing to its high electrical and thermal energy efficiency, while biomass boiler is used as a supplement.

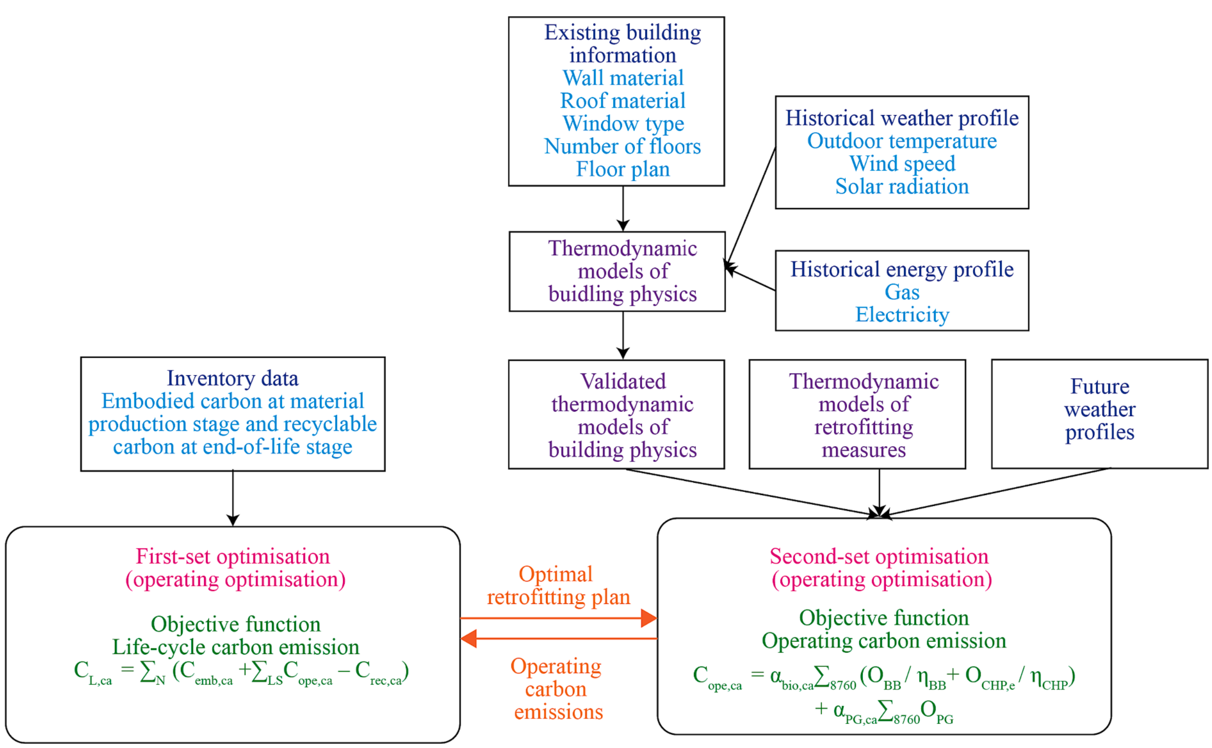


Fig. 1. Flowchart of the proposed integrated passive and active retrofitting approach.

3.2.1. Design variables

Design variables of second-set optimisation consist of operating capacity of biomass cogeneration system $O_{CHP,e}$ and biomass boiler O_{BB}, charging $O_{ES,ch}$ and discharging rate $O_{ES,dch}$ of electricity storage, as well as imported rate of electricity from power grid O_{PG}. The operating capacity of biomass cogeneration system, biomass boiler and electricity storage are optimised in order that they can cooperate better with each other. In this way, the operating scheme of each active retrofitting measure is determined by their optimal coordination with each other.

3.2.2. Objective function

The yearly operating carbon emissions $C_{ope,ca}$ is minimised by the second-set optimisation, which is one of the components in Eq. (1). As solar panel, solar heating system and wind generator convert clean sources (i.e., solar and wind energy) into electrical and thermal energy, there is no extra operating carbon emission. Electricity storage is an energy conversion device and does not generate carbon emissions. Therefore, the operating carbon emissions mainly come from the biomass boiler, CHP system and power grid [49], as shown in Eq. (2).

$$\min C_{ope,ca} = \alpha_{bio,ca}\sum_{8760}(O_{BB}/\eta_{BB} + O_{CHP,e}/\eta_{CHP}) + \alpha_{PG,ca}\sum_{8760}O_{PG} \quad (2)$$

The yearly operating carbon emissions from biomass depends on the year-round operating capacity of biomass boiler O_{BB}, and biomass CHP system $O_{CHP,e}$, efficiency of biomass CHP system η_{CHP} and biomass boiler η_{BB}, as well as carbon factor of biomass $\alpha_{bio,ca}$. Year-round operating carbon emissions from power grid depend on the importation rate from power grid O_{PG} and carbon factor of power grid $\alpha_{PG,ca}$. Once the design variables such as hourly operating capacities of biomass boiler O_{BB}, biomass CHP system $O_{CHP,e}$ and electricity importation rate from power grid O_{PG} are estimated, the total carbon emissions for 8760 h (i.e., 1 year) can be obtained.

3.2.3. Optimisation constraints

Building energy demands balance should be satisfied by matching energy supply from various energy devices and building energy demands [49,50]. The heat and electricity balances are presented in Eq. (3) and Eq. (4), respectively, while operating status of electricity storage is presented in Eq. (5).

$$E_h - O_{WI} - O_{RI} \le O_{BB} + O_{SH} + O_{CHP,h} \quad (3)$$

$$E_e + O_{ES,ch} \le O_{CHP,e} + O_{PV} + O_{WT} + O_{ES,dch} \quad (4)$$

$$O_{ES}^{t+1} = O_{ES}^{t} + O_{ES,ch}^{t} - O_{ES,dch}^{t} \quad (5)$$

The actual outdoor air dry-bulb temperature, design area of roof insulating material D_{RI}, and design area of wall insulating material D_{WI} determines the reduction of heating demand through the roof insulating material O_{RI} and wall insulating material O_{WI}. The energy generating rate from solar panel O_{PV}, solar heating system O_{SH} and wind generator O_{WT} mainly depends on meteorological conditions like solar radiation and wind speed, along with corresponding design parameters such as D_{PV}, D_{SH} and D_{WT}. The operating capacity of biomass boiler O_{BB} and biomass cogeneration system $O_{CHP,e}$ cannot exceed their design capacities (D_{CHP}, D_{BB}) determined from the first-set optimisation. In addition, stored energy in electricity storage O_{ES}^{t} at any time t cannot exceed its design capacity D_{ES}. Furthermore, charging $O_{ES,ch}$ and discharging $O_{ES,dch}$ of electricity storage should not take place simultaneously.

3.3. Particle swarm optimisation (PSO) algorithm

Developed by Eberhart and Kennedy, PSO algorithms are broadly employed to solve sophisticated engineering problems thanks to its robustness in solving continuous problems [51]. Its primary strengths include higher convergence speed and less computing load [52]. As design variables in both sets of optimisation belong to continuous problem, PSO is used in both first-set optimisation and second-set optimisation [53]. The PSO algorithm has also proven to be applicable in previous research works [47,48].

For the first-set optimisation, the particles represent a population of retrofitting plans. In other words, each particle indicates a set of 8 design variables (i.e., D_{RI}, D_{WI}, D_{PV}, D_{SH}, D_{WT}, D_{CHP}, D_{BB} and D_{ES}). The fitness function is whole-life carbon emissions as calculated from Eq. (1).

For the second-set optimisation, the particles represent a population of operating schedules. To reduce the computational burden of a single iteration and to consider the weekly pattern of energy consumption, 52 weekly operating schedules are optimised respectively. Therefore, each particle indicates the weekly schedule ($7 \times 24 = 168$ time steps) for 5 operating variables (O_{BB}, $O_{CHP,e}$, $O_{ES,ch}$, $O_{ES,dch}$, O_{PG}). As the operating schedule is determined at hourly base, there are 5×168 variables in each particle. And the fitness value of each particle is estimated according to optimisation objectives function in Eq. (2).

3.4. Retrofitting evaluation indices

The whole-life energy consumption $C_{L,en}$ and economic costs $C_{LC,co}$ are calculated according to Eq. (6) and (7), respectively:

$$C_{L,en} = C_{emb,en} + \sum_{LS} C_{ope,en} - C_{rec,en} \quad (6)$$

$$C_{L,co} = C_{emb,co} + \sum_{LS} C_{ope,co} \quad (7)$$

$C_{emb,co}$ is the total investment cost, $C_{emb,en}$ is embodied energy resulted from manufacturing various retrofitting materials, while $C_{rec,en}$ is the recyclable embodied energy at the end of the material's lifespan.

Payback time of investment cost Y_{co}, embodied carbon Y_{ca}, and embodied energy Y_{en} indicates how many years the corresponding investment cost can be recouped through reduction in operating cost, embodied energy can be recouped through decrease in energy consumption and embodied carbon can be recouped through decline in operating carbon emissions, respectively. It can be estimated from Eq. (8):

$$Y_k = C_{emb,k}/(C_{ope,k,pre} - C_{ope,k}) \quad (8)$$

where k represents co, ca, or en, respectively. For example, when $k = co$, Eq. (8) is used to calculate the payback time of investment cost, and $Y_{co} = C_{emb,co}/(C_{ope,co,pre} - C_{ope,co})$. $C_{ope,co,pre}$, $C_{ope,en,pre}$ and $C_{ope,ca,pre}$ is the operating cost, carbon emissions and primary energy usage before retrofitting. $C_{ope,co}$, $C_{ope,en}$ and $C_{ope,ca}$ is the operating cost, carbon emissions and primary energy usage after retrofitting, which can be estimated from operating status of each retrofitting measure.

Ratio of cost savings-to-investment r_{co}, energy reduction-to-embodied r_{en} and carbon reduction-to-embodied r_{ca} is defined in Eq. (9):

$$r_k = \sum_{LS}(C_{ope,k,pre} - C_{ope,k})/C_{emb,k} \quad (9)$$

4. Case study of a real-world office building

An actual office building is referred to test the effectiveness of this integrated passive and active retrofitting approach. Historical gas and electricity consumption profile, current building design parameters, historical meteorological profile, and life-cycle inventory information from a variety of sources are collected and adopted in this study. Due to data availability from the real-world building, 2018 is selected as the case study year. Historical gas and electricity consumption profile and historical meteorological profile collected in 2018 is used to validate the developed thermodynamic model. Moreover, historical meteorological profile in 2018 is adopted as the representative weather profile for estimating the carbon emissions during its operating stage, as well as the renewable energy production during post-retrofitting stage.

4.1. General building information and historical energy demand

The real-life representative office building (Costain House), situated at Maidenhead (UK) is employed for performance assessment of this integrated passive and active retrofitting approach. All the building related information is provided by the building engineers and building management system of Costain House, including the floor plan (i.e., Fig. 2), perspective view (i.e., Fig. 3), as well as natural gas and electricity consumption (i.e., Fig. 5). Costain House is a 3-storey building and has an overall floor area of 1499 m^2, as well as total external wall area of 605 m^2. Currently, heating demand is supplied by a boiler fuelled by natural gas; cooling demand is supplied by the conventional chiller using electricity, while electrical energy purely relies on centralised power grid. U-value of its top roof and exterior wall is 0.00245 kW/m^2, while heat transfer coefficient of double-glazed window is 0.00169 kW/m^2K. The front door is facing north, while the window-to-wall ratio is 2.

Meteorological profile of Maidenhead in 2018 is collected from the local weather station and presented in Fig. 4, including outdoor temperature, wind speed and solar irradiance.

Natural gas consumption was initially measured in m^3/s using the gas meter and converted to kW according to its low heating value. The yearly consumption in 2018 was 1,015,478 kWh and 568,838 kWh for electricity and gas, with the peak at 279 kW and 211 kW, respectively. Usage rates of electricity and natural gas (measured in kW), along with monthly total consumption (measured in kWh), are shown in Fig. 5.

4.2. Retrofitting measures and corresponding thermodynamic models

According to the building facility manager, there is a space of 3000 m^2 for solar panel and solar heating system. The maximum allowable design power is 150 kW and 250 kW for the CHP system and wind generator, respectively. The maximum permissible design capacity for electricity storage is 600 kWh. The maximum allowable design capacity of CHP system, wind generator and electricity storage are determined by the facility managers and building engineers at Costain House based on the actual available space of the building.

The reduction of heat loss through wall and roof insulating material is determined by first principles [54] of heat conduction due to the fact that envelope insulating materials only affects sensible heating demand. Moreover, electrical energy production from solar panel [55], thermal heat from solar heating system [56], energy behaviour of biomass-fuelled cogeneration system [57], biomass boiler [58] and electricity storage [59] can be estimated using corresponding thermodynamic models. Electricity power from the wind generator can be predicted using its practical performance data. This study is based upon the situation that excess heat and electricity cannot be sold back to centralised grids. This assumption is made to simplify the process of measuring whole-life carbon because it is difficult to measure the carbon credit by feeding electricity and heat to corresponding grids. Also, it is not well-rewarded in the UK. The corresponding technical parameters of each retrofitting measure can be found in [45].

Electricity power from the wind generator and solar panel, as well as the heating power from the solar heating system is estimated from 2018 meteorological profile. The year-round electricity power from the wind generator with nominal capacity of 1 kW, heat from the solar heating system with design area of 1 m^2 and electricity power from solar panel of design area of 1 m^2 is summarised in Fig. 6(a), Fig. 6(b) and Fig. 6(c), respectively. The energy production is 1502, 876 and 138 kWh for the simulated year from wind generator, solar heating system and solar panel, respectively. The peak thermal power production from solar heating system is 0.71 kW, while the solar panel's peak electricity generating rate is 0.11 kW. Energy profiles of wind generators, solar heating systems and solar panels depend on the local meteorological profile. In practical application, there might exist slight differences in energy profiles among different geographical locations. If local meteorological profiles are not available, combined regional or national profiles can be referred to.

4.3. Inventory information

Inventory information indicates carbon emissions and energy use occurred at material manufacturing and production stage. The collected inventory data is referred to [46,47,59]. The life span of insulation materials, PV panel, wind turbine, solar heater, CHP system and biomass boiler is 60, 25, 20, 20, 15 and 20 years, respectively.

5. Performance evaluation of integrated passive and active retrofitting optimisation approach

At the beginning, effectiveness of PSO algorithm is assessed

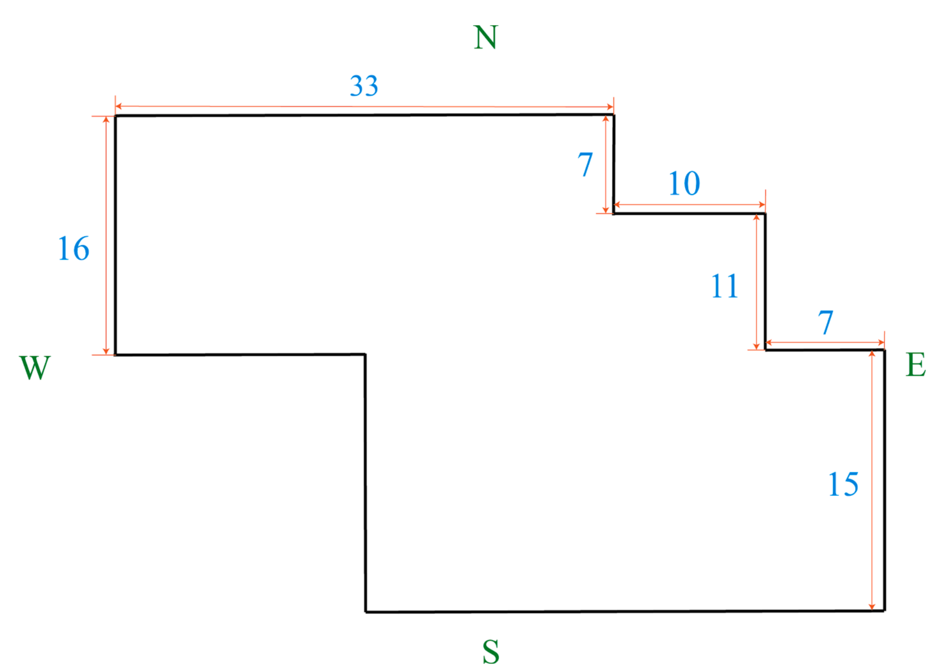


Fig. 2. Floor plan and orientation of Costain House (the case study building).

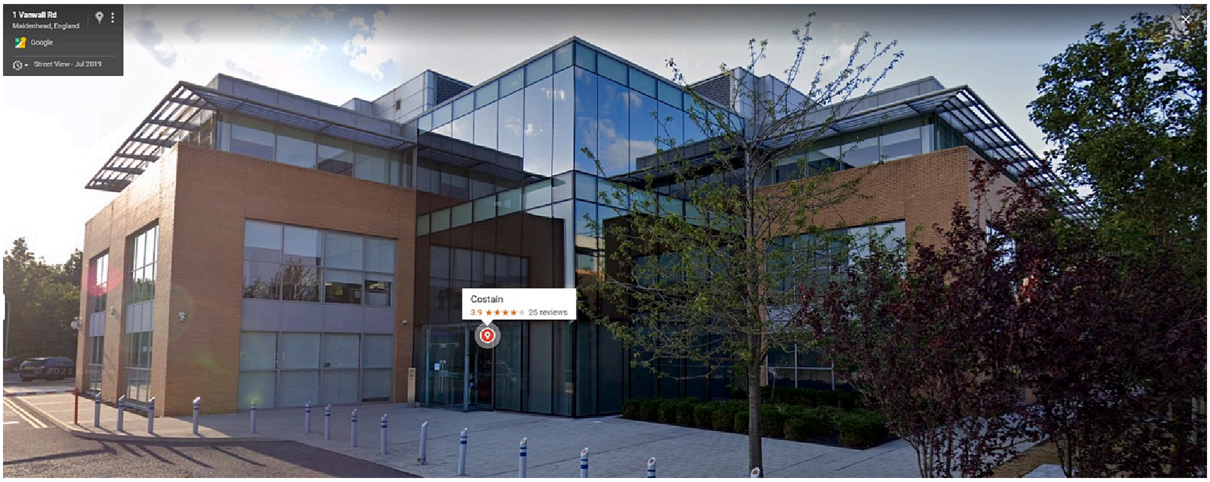


Fig. 3. Perspective view of Costain House (the case study building).

according to its convergence. Secondly, results from two sets of optimisation algorithms are analysed. Thirdly, comparison is conducted between optimisation results from the proposed retrofitting approach and up-to-date retrofitting strategies. Those up-to-date retrofitting measures include operating zero-carbon retrofitting strategy, “design optimisation only” retrofitting strategy, and “operating carbon emissions optimisation only” retrofitting strategy.

5.1. Performance evaluation of PSO algorithm

PSO algorithm is adopted to find appropriate design variables to minimise the whole-life carbon emissions $C_{L,ca}$ at the first-set optimisation and operating carbon emissions $C_{ope,ca}$ at the second-set optimisation. $C_{ope,ca}$ is continuous feedback from second-set optimisation to first-set optimisation. The PSO parameters are recapped in Table 2, while the convergence performance is illustrated in Fig. 7. The first-set optimisation achieves convergent after 120 iterations while the second-set optimisation only needs 30 iterations to reach convergent. Although the total time consumption of the first-set optimisation and second-set optimisation is nearly 24 h, it is applicable in practice as this retrofitting optimisation is conducted offline. There is no real-time requirement for this optimisation.

5.2. Performance evaluation of the integrated passive and active retrofitting approach

From the first-set design optimisation, design capacities of each retrofitting measure are summarised in Table 3. According to Section 3.1, the electricity demand is larger than the heating demand. Rated efficiency of solar heating system (i.e., 44%) is larger than that of solar panel (i.e., 12%), while rated electrical efficiency (i.e., 12%) of cogeneration system is smaller than its thermal efficiency (i.e., 58%). As a result, the design area of solar panel (i.e., 2,817 m^2) is almost 21 times higher than that of the solar heating system (i.e., 129 m^2). Meanwhile, the wind generator can provide additional electricity supply.

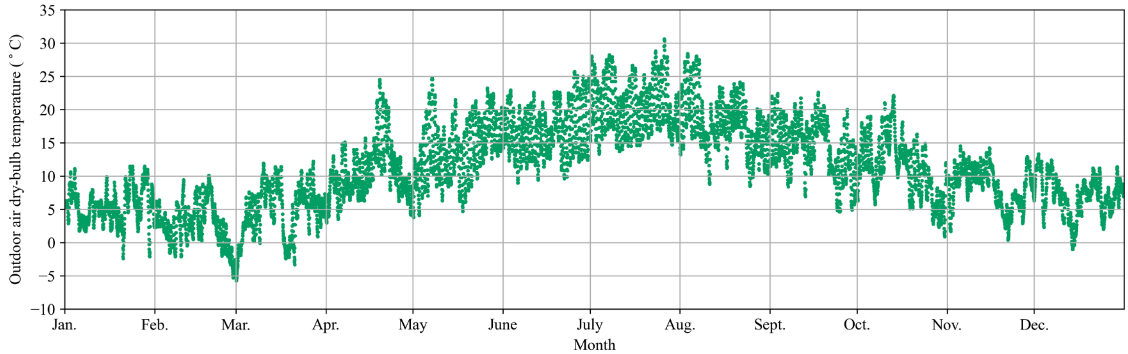
The operating capacity allocation of heating and electricity supply during a winter week and a summer week can be determined through the second-set optimisation, as summarised in Fig. 8. The bars indicate the energy supply from different energy devices, while the curve indicates the energy demand.

- The electricity produced from the wind generator and solar panel is determined by wind speed and solar radiation, respectively. If the total amount of electricity generated by wind generator and solar panel is not enough for the electricity demand, biomass cogeneration system would be operated, and electricity storage would be discharged. Power grid can also provide additional electricity while necessary. On the contrary, if electricity generated by wind generator, solar panel and biomass cogeneration system is larger than demand, the excess electricity would be stored in the electricity storage. In winter, as identified from Fig. 7(a), electricity from solar panel is much lower compared to that from the wind generator. This is mainly due to the small solar radiation but large wind speed. In summer, as shown in Fig. 7(c), electricity from solar panel is much higher than that from wind generator. This is due to the large solar radiation but small wind speed. Overall speaking, accompanied by centralised power grid and electricity storage, solar panel, wind generator and biomass CHP system can work effectively at supplying electricity demand.
- The thermal energy from the solar heating system and biomass cogeneration system would satisfy the heating demand. In winter, as shown in Fig. 7(b), heating demand is comparatively high due to low temperature while heat generated by solar heating system is low owing to low solar radiation. Thus, a large portion of thermal energy would be satisfied by biomass cogeneration system. In summer, as shown in Fig. 7(d), due to larger heat generated by solar heating system, the total amount of heat is much larger than the actual heating demand. According to [47], the increased embodied carbon caused by heat storage cannot be made up of by its shifting ability of heating demand. Moreover, heat production from CHP system is constantly larger than the actual heat demand, as shown in Fig. 7(b) and 7(d). Therefore, if the total heat generated by solar heating system and CHP system is larger than the actual heating demand, it is deemed as waste.

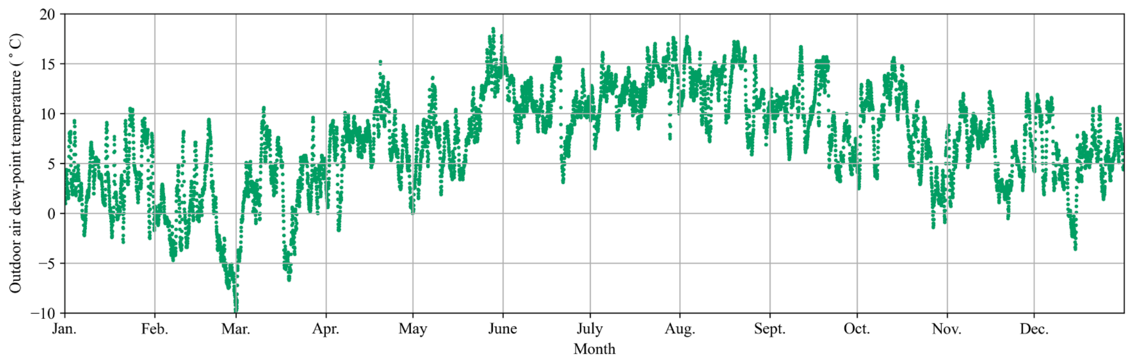
The whole-life economic, energy and environmental performance before and after retrofitting is summarised in Table 4. There exist 72%, 85% and 91% reduction in yearly operating cost, carbon emissions and energy use, respectively. Although retrofitting measures will cause additional investment cost, embodied carbon and embodied energy, there is 44%, 74%, and 68% decline in total costs, carbon emissions and primary energy usages when its lifelong performance is considered.

5.3. Performance comparison with operating zero-carbon building

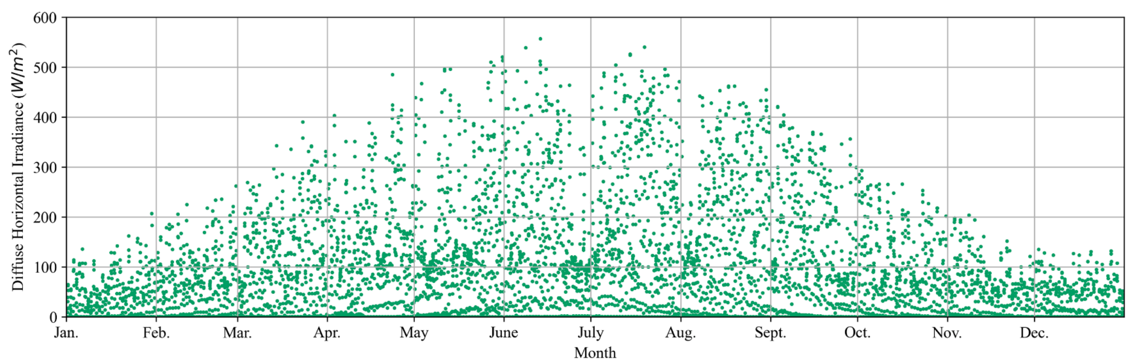
The objective of state-of-the-art operating zero-carbon building retrofitting strategy is to get the year-round total operating greenhouse gas emissions to be zero [61–63]. In general, it does not set the allowable design area for solar panel and solar heating system, and the maximum design capacity for wind generator. Thus, renewable energy devices are distributed both on-site and off-site to provide heat or electricity for the



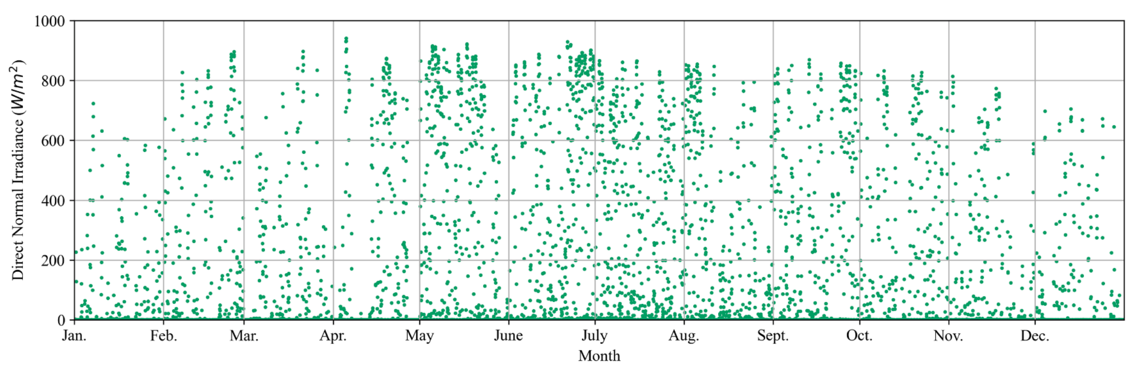
(a) Outdoor air dry-bulb temperature



(b) Outdoor air dew point temperature

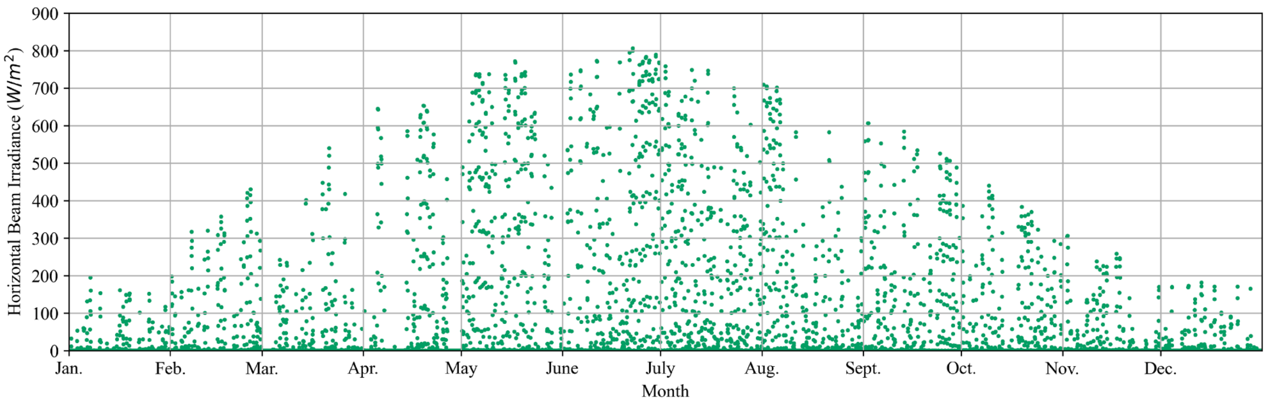


(c) Diffuse horizontal solar radiation



(d) Direct normal solar radiation

Fig. 4. Meteorological profile of Maidenhead in 2018.



(e) Horizontal beam solar radiation

Fig. 4. (*continued*).

buildings [64]. Four reference operating zero-carbon retrofitting strategies are implemented on the same case study building as described in Section 3.1. For the first three reference zero-carbon retrofitting strategies, solar panel, wind generator and solar heating system are individually adopted to offset the operating carbon emission, respectively. In the 4th reference zero-carbon retrofitting strategy, solar panel, solar heating system and wind generator is simultaneously adopted at its optimal design value. A summary of performance assessment results is shown in Table 5. Some of these reference retrofitting strategies do have better whole-life performance than the proposed approach because they are based on the ideal scenario. For example, actual installation area of solar panel is 12,892 m^2 in Reference 1, nominal capacity of wind generator is 1,182 kW in Reference 2, while the design area of solar heating system is 5,068 m^2 in Reference 3. In reality, these design areas and design power might be constraint due to limited space around the office building.

5.4. *Performance comparison with "design optimisation only" retrofitting strategy*

To demonstrate the effectiveness of the second-set operating optimisation, several "design optimisation only" retrofitting approaches are adopted as reference. These "design optimisation only" retrofitting strategies only conduct the first-set design optimisation. To be more specific, design variables of solar panel, solar heating system, CHP system, wind generator and electricity storage are determined when conventional operating strategies are adopted [17,22,31,32,34,40–42,46–48]. These conventional operating strategies include following electricity load strategy, following heat load strategy, basic load with electricity storage, and basic load without electricity storage. Following electricity load strategy means that biomass cogeneration system is operated according to the actual electrical energy demand. Following heat load strategy refers to the fact biomass cogeneration system is operated according to the actual thermal energy demand. The basic load strategy means that CHP system is operated constantly at its full load. Performance evaluation of these "design optimisation only" retrofitting strategies is summarised in Table 6. The proposed retrofitting approach can reduce 5.36%-34.37% whole-life energy consumption and 4.31%-51.10% carbon emission compared to "design optimisation only" retrofitting strategies, proving the effectiveness of this integrated passive and active retrofitting approach in obtaining optimal whole-life performance. It is also noticed that the payback time of cost, carbon and energy of this proposed integrated passive and active retrofitting approach is slightly longer than that of the "design optimisation only" retrofitting strategy with basic load and without electricity storage. It is mainly owing to the high investing cost, high embodied carbon and large embodied energy of electricity storage materials. Once more suitable materials have been identified for electricity storage, the payback year of the proposed retrofitting approach can be further reduced.

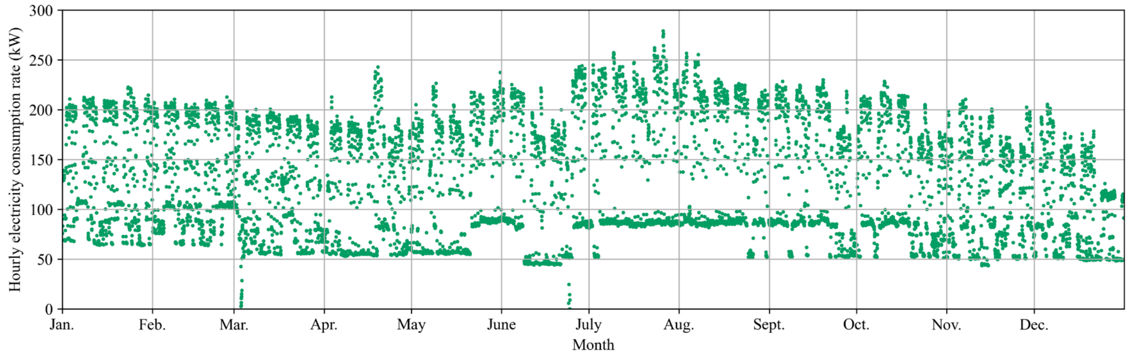
5.5. *Performance comparison with "operating carbon emissions optimisation only" retrofitting strategy*

To demonstrate the effectiveness of the whole-life carbon optimisation, a reference "operating carbon optimisation only" retrofitting strategy is adopted. To be more specific, the only optimisation objective of the reference retrofitting strategy is the year-round operating carbon emission, while the embodied carbon of retrofitting measures is not considered [12,13,16–18]. The retrofitting results are summarised in Table 7. Compared to the reference "operating carbon emission only" retrofitting strategy, there is 11.92%, 10.55%, and 10.48% reduction in whole-life cost, whole-life energy usage and whole-life carbon emissions, respectively. A 16.16%, 18.11% and 14.90% reduction in payback year of investment cost, payback year of embodied energy and payback year of embodied carbon is also witnessed. This is also reflected on 33.90%, 26.89% and 22.66% increase in the ratio of cost savings-to-investment, energy reduction-to-embodied energy, and carbon reduction to embodied carbon, respectively. Therefore, from a whole-life point of view, the proposed integrated passive and active retrofitting approach will result in better performance.

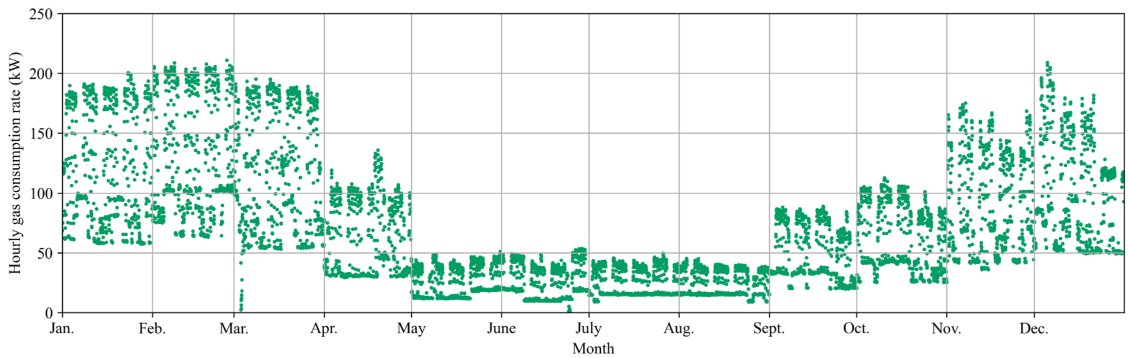
6. Practical implication, limitation and future study

This paper describes an integrated passive and active retrofitting approach to identify environmentally friendly retrofitting options for commercial buildings. Unlike various literatures which used simulation data and heat degree day, a real office building in the UK is utilised to test the robustness and effectiveness of the proposed integrated passive and active retrofitting approach. Gas and electricity consumption profiles, design parameters at pre-retrofitting stage, as well as local meteorological information and inventory information are adopted to fully represent the real-world case. As a result, this integrated passive and active retrofitting approach can be adopted in various climatic and geographical areas for different types of buildings. The effective retrofitting approach can play a dominant role in various practical applications.

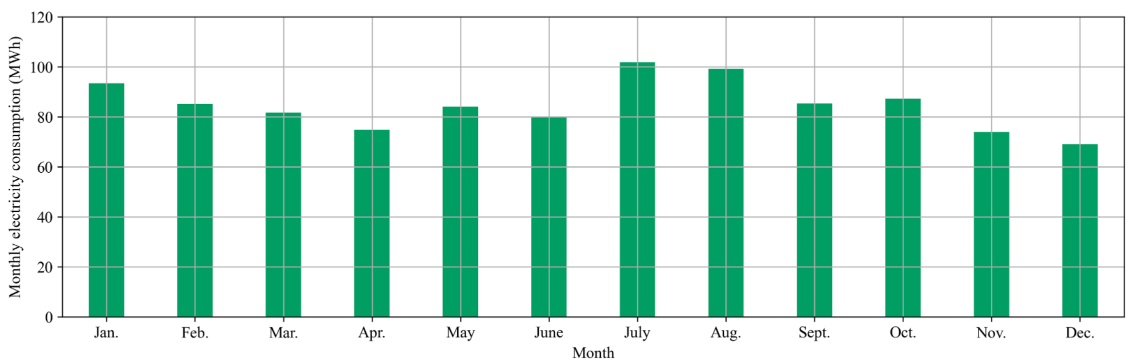
First of all, this integrated passive and active retrofitting approach can assist facility and building managers in obtaining an in-depth insight into different retrofitting options, such as their total carbon emissions and energy consumption during the entire life cycle. Thus, it helps them make effective decisions and choose optimal retrofitting solutions.



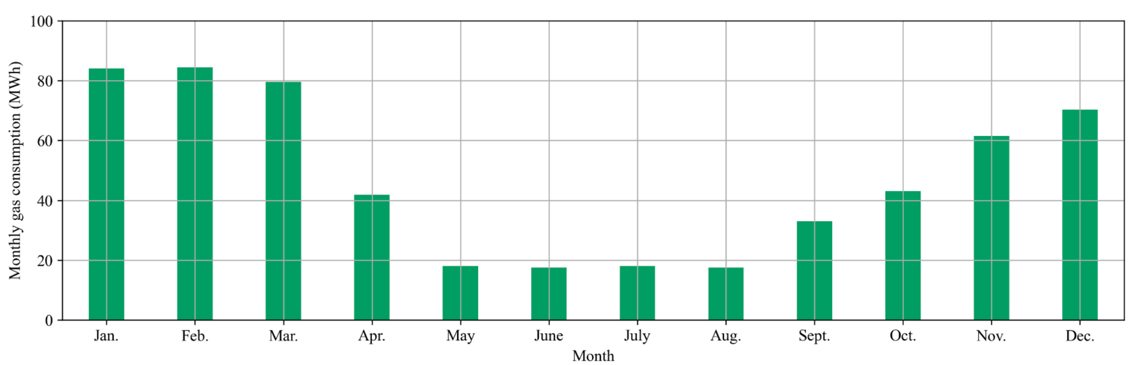
(a) Hourly electricity consumption rate



(b) Hourly gas consumption rate

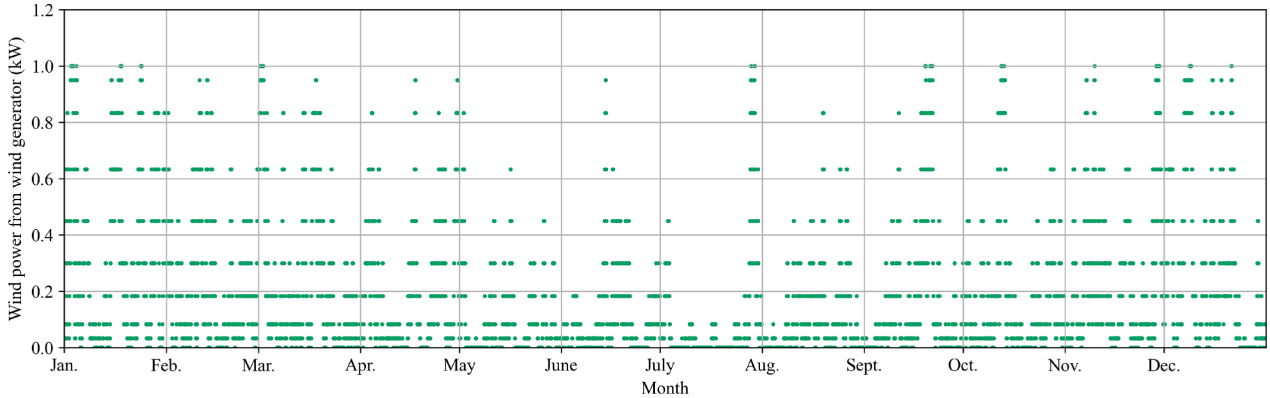


(c) Monthly electricity consumption

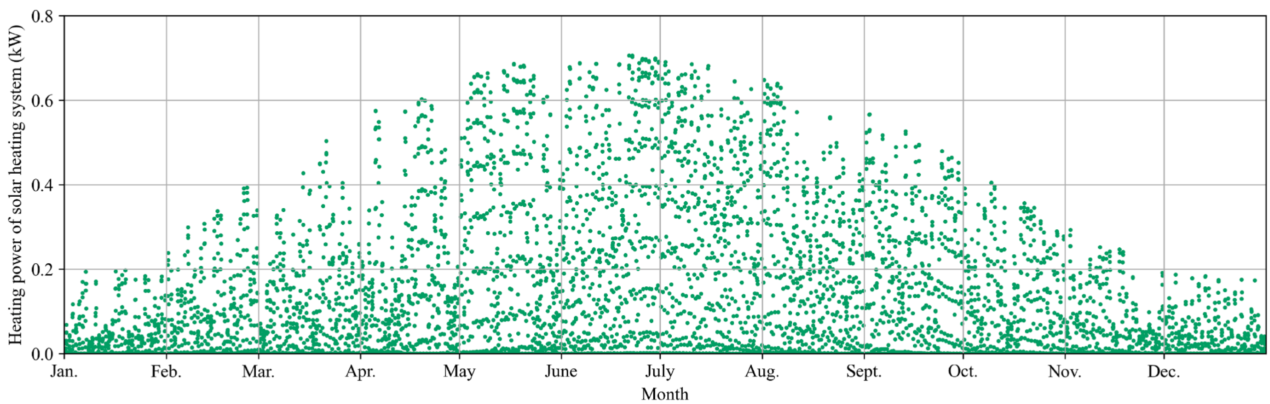


(d) Monthly gas consumption

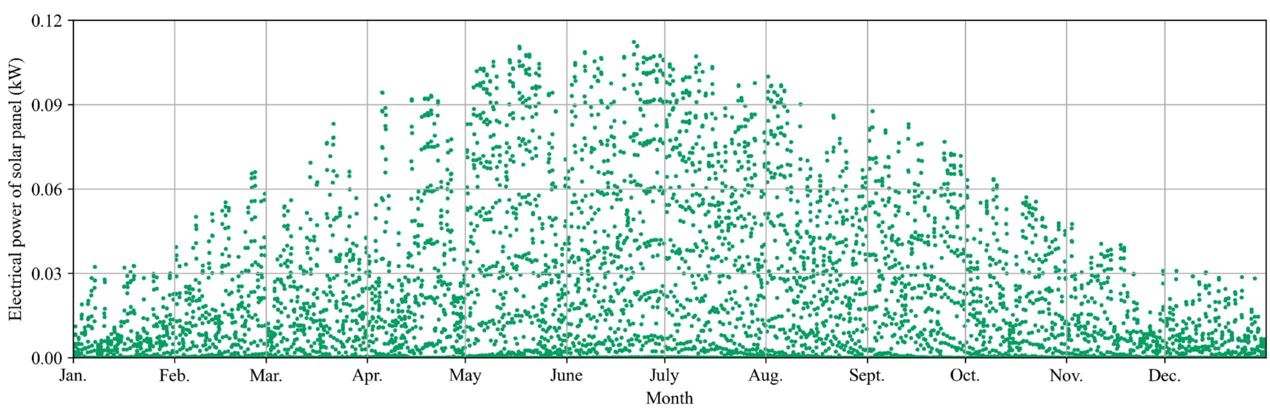
Fig. 5. Natural gas and electricity consumption of Costain House in 2018.



(a) Hourly electricity generation rate from wind generator



(b) Hourly heat generation rate from solar heating system



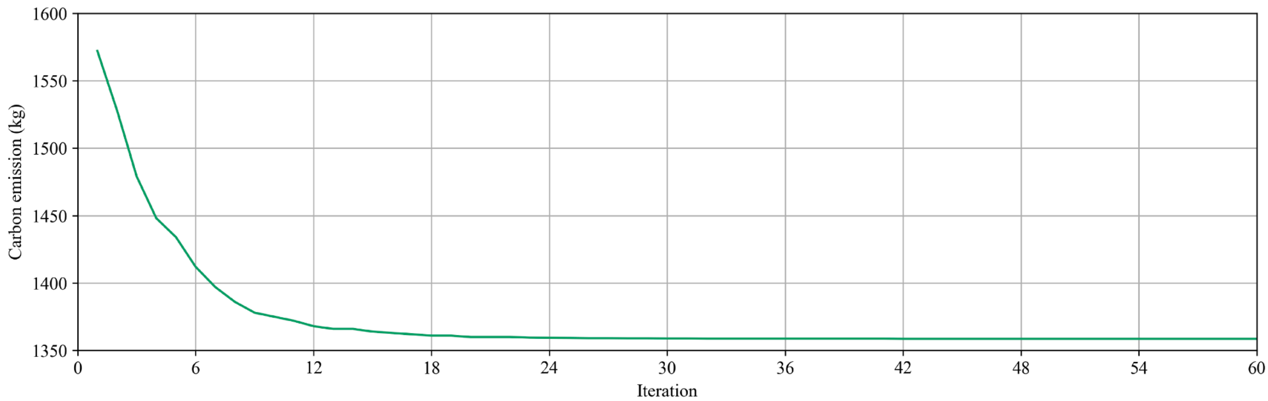
(c) Hourly heat generation rate from solar panel

Fig. 6. Year-round renewable energy production rate.

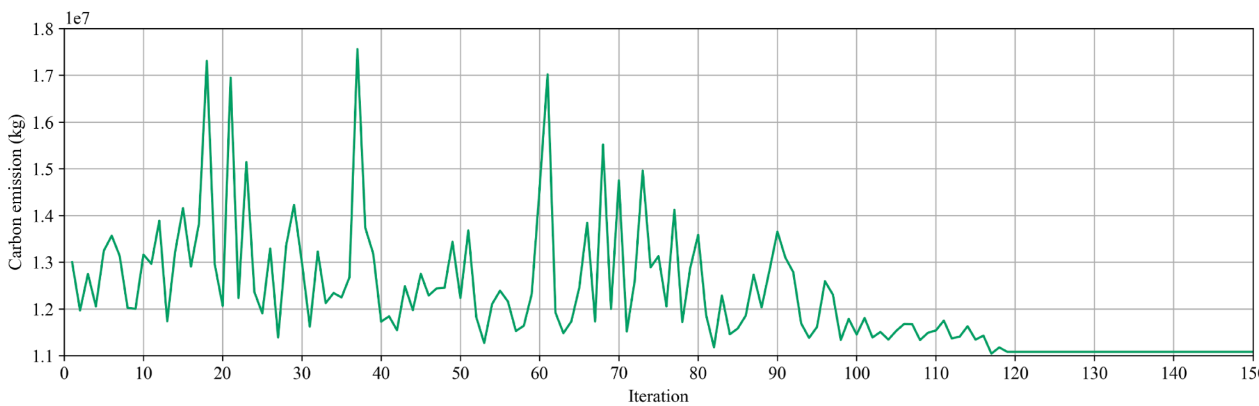
Table 2
Hyper-parameters of PSO algorithm [60].

Inertia weight γ_1		0.5
Cognitive parameter γ_2		2
Social parameter γ_3		2
Population size	First-set	20
	Second-set	500
Maximum number of iterations	First-set	150
	Second-set	60
Number of design variables	First-set	5
	Second-set	5 × 168

Secondly, the second-set operating optimisation can play a dominate role in daily energy management at the post-retrofitting stage. Based on accurate energy demand forecast, optimal operating schedules of each energy device can be determined. Through appropriate control of active energy devices, daily energy usage and carbon emissions can be cost-effectively minimised. For new buildings, it is also essential to consider the integrated design and operating optimisation to minimise whole-life cost, energy use and carbon emissions. In addition, it can be revised and adopted at design stage to develop building information models and satisfy corresponding energy performance requirement. Last but not least, the proposed retrofitting optimisation approach can



(a) First-set optimisation



(b) Second-set optimisation

Fig. 7. Convergence performance of PSO for two sets of optimisation processes.

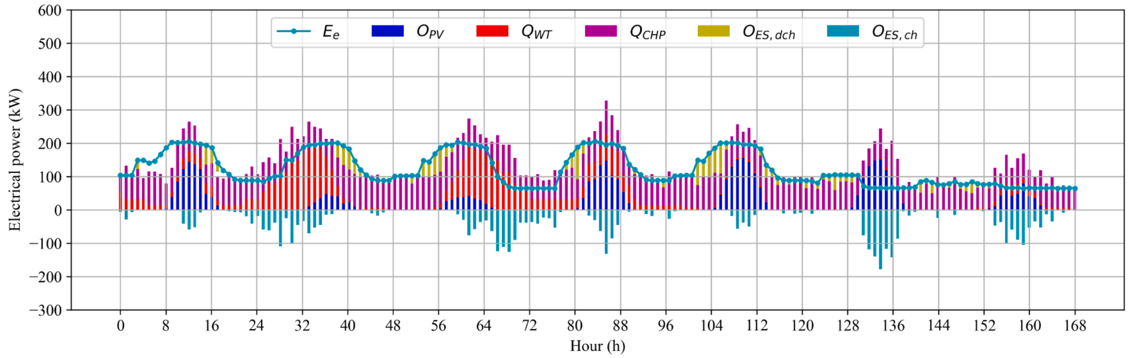
Table 3
Retrofitting plan estimated by the proposed retrofitting strategy.

Retrofitting measures	Roof insulating material	Wall insulating material	Solar panel	Solar heating system	Biomass cogeneration system	Wind generator	Biomass boiler	Electricity storage
Unit	m^2	m^2	m^2	m^2	kW	kW	kW	kWh
Value	1,499	605	2,817	129	100	178	0	566

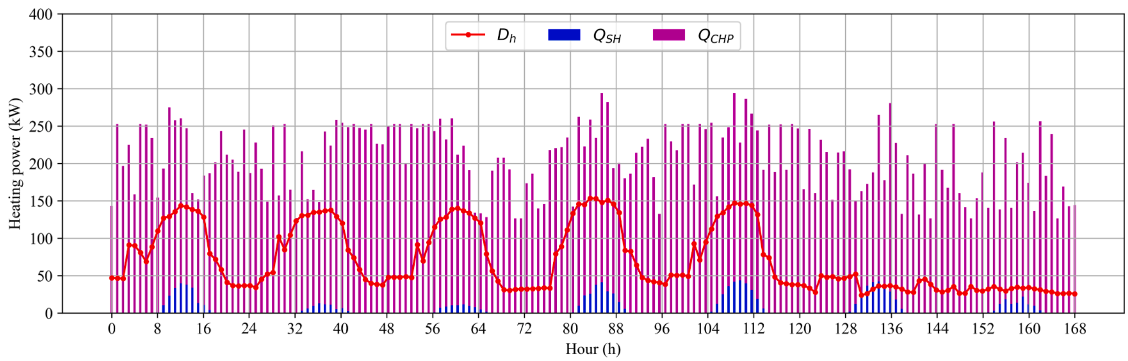
contribute to whole-life economic, energetic and environmental benefits. By reducing energy usage and carbon emissions of a large number of office buildings, global resources crisis and climate change problems can be effectively mitigated.

As the scope of this research is proposing an effective and innovative integrated passive and active retrofitting approach, the following limitations may need to be further addressed in future practical applications.

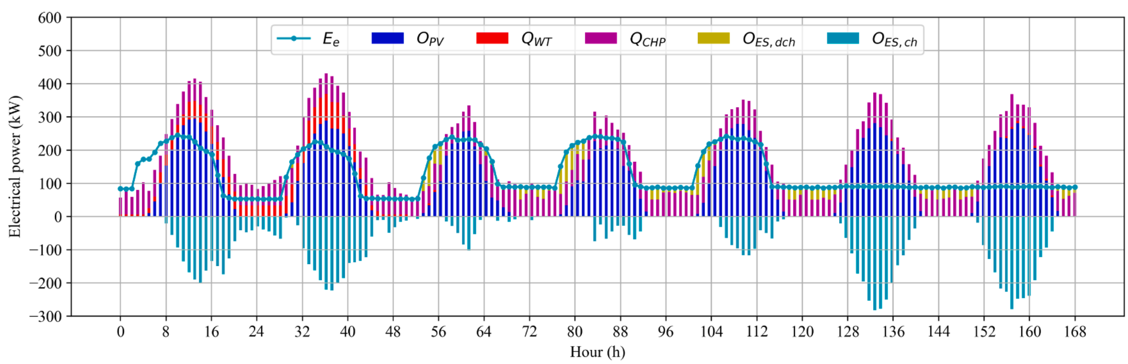
- The inventory information of the refurbishment materials and energy devices is gathered from several sources and references owing to the current absence of available life-cycle inventory techniques. The process analysis-based life-cycle inventory may suffer from truncation error. In practical application, such inventory information should be collected from local supply chain and inventory database.
- Only one type of roof insulating material, wall insulating material, solar panel, solar heating system, wind generator, biomass-fuelled cogeneration system, biomass boiler is investigated in this study. The types of each retrofitting measure should be expanded according to the actually available supply chain. Other available retrofitting measures such as ground source heat pumps and concentrating photovoltaic thermal collectors [7] can also be considered. Nevertheless, the proposed retrofitting approach can be easily expanded on other retrofitting measures.
- Due to the lack of typical metrological weather profile at the specific site, the historical weather profile of a single year (i.e., 2018) is obtained from a nearby local weather station. The historical weather in this specific single year is used to estimate the building's future energy performances. However, the weather profile might be variable in each year, and it may also change due to climate change. In future works, the projected future weather profile can be used to account for the effects of climate change.
- This proposed retrofitting approach can also be modified and extended to provide guidance in designing new low-carbon buildings. Moreover, at the new building design stage, atrium can be adopted to increase the natural daylighting [65]; biomimicry approach can be adopted to enhance climatic adaptation and local biodiversity can be used as a library of organisms [66]; natural ventilation can also be implemented to reduce cooling load and enhance human comfort [67]. These new methods should also be considered when designing net-zero or low carbon buildings.
- Biomass is effective at reducing carbon emissions. If the sources of biomass are limited, natural gas can be used as an alternative fuel for



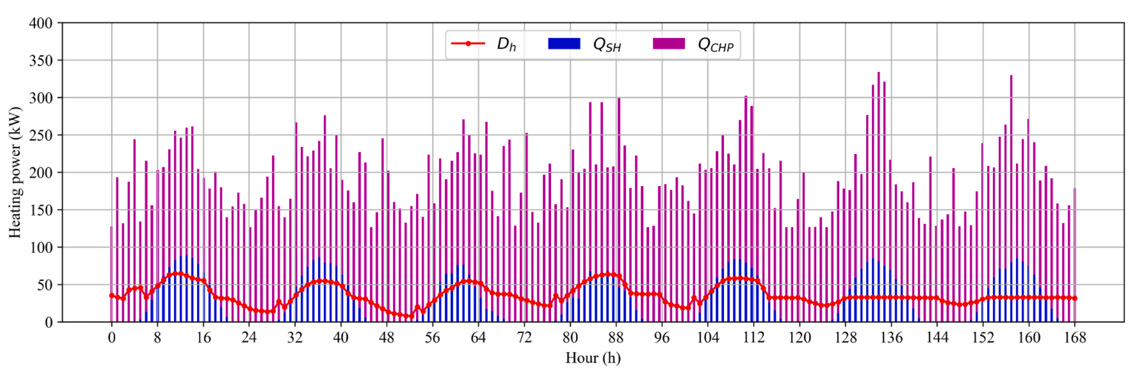
(a) Electrical power allocation during a typical week in winter.



(b) Heating power allocation during a typical week in winter.



(c) Electrical power allocation during a typical week in summer.



(d) Heating power allocation during a typical week in summer.

Fig. 8. Optimisation results of second-set optimisation.

Table 4
While-life economic, energy and environmental performance of the retrofitted building.

Performance	Whole-life cost	Year-round cost	Investment cost	Whole-life energy	Year-round energy	Embodied energy	Whole-life carbon	Year-round carbon	Embodied carbon
Unit	($\times 10^6$ £)			($\times 10^7$ MJ)			($\times 10^6$ kg)		
Post-retrofitting	5.47	0.05	2.75	21.17	0.17	10.93	11.02	0.06	7.20
Pre-retrofitting	9.81	0.16		67.12	1.12		42.22	0.70	
Reduction	44%	72%		68%	85%		74%	91%	

Table 5
Performance comparison between the retrofitted building and zero carbon buildings.

Retrofitting options	Reference 1	Reference2	Reference 3	Reference 4	Proposed approach
	All Solar panel	All wind generator	All solar heating system	Combination	
Roof insulating material (m^2)	1,499	1,499	1,499	1,499	1,499
Wall insulating material (m^2)	605	605	605	605	605
Solar panel (m^2)	12,892	0	0	928	2,817
Solar heating system (m^2)	0	0	5,068	2,072	129
Wind generator (kW)	0	1,182	0	694	178
CHP system (kW)	0	0	0	0	100
Electricity storage (kWh)	0	0	0	0	566
Biomass boiler (kW)	0	0	0	0	0
Whole-life cost ($\times 10^6$ £)	6.79	3.56	0.59	3.29	5.47
Whole-life energy usage ($\times 10^7$ MJ)	7.08	20.54	2.09	13.58	21.17
Whole-life carbon emissions ($\times 10^6$ kg)	3.46	24.64	1.69	15.34	11.02
Payback year of investment cost	41.55	21.79	3.64	20.15	23.25
Payback year of embodied energy	6.33	18.36	1.86	12.14	11.53
Payback year of embodied carbon	4.92	28.03	2.40	21.80	11.25
Cost savings-to-investment	0.44	1.75	15.51	1.98	1.58
Energy reduction-to-embodied	8.48	2.27	31.17	3.94	4.20
Carbon reduction-to-embodied	11.20	0.89	24.05	1.75	4.33

Table 6
Performance comparison between the proposed retrofitting strategy and conventional operating strategy-based retrofitting approach.

Retrofitting measures	"Design optimisation only" retrofitting strategies				Proposed retrofitting approach
	Following electricity load strategy	Following heat load strategy	Basic load with electricity storage	Basic load without electricity storage	
Roof insulating material (m^2)	1,499	1,499	1,499	1,499	1,499
Wall insulating material (m^2)	605	605	605	605	605
Solar panel (m^2)	1,433	2,613	2,251	1,709	2,817
Solar heating system (m^2)	74	387	0	0	129
CHP system (kW)	119	22	49	57	100
Wind generator (kW)	190	321	210	185	178
Electricity storage (kWh)	0	0	571	0	566
Biomass boiler (kW)	143	189	54	34	0
Whole-life cost ($\times 10^6$ £)	4.82	6.27	5.48	5.70	5.47
Whole-life energy usage ($\times 10^8$ MJ)	2.24	3.23	2.35	2.60	2.12
Whole-life carbon emissions ($\times 10^7$ kg)	1.16	2.27	1.59	1.57	1.11
Payback year of investment cost	18.40	25.30	20.70	18.80	23.25
Payback year of embodied energy	12.70	13.60	9.40	9.20	11.53
Payback year of embodied carbon	11.50	18.20	13.60	10.70	11.25
Cost savings-to-investment	2.25	1.37	1.90	2.19	1.58
Energy reduction-to-embodied	3.72	3.42	5.36	5.50	4.20
Carbon reduction-to-embodied	4.21	2.30	3.42	4.60	4.33

CHP system. The carbon emissions from natural gas might be higher than that from biomass. Thus, the entire retrofitting design process should be conducted again.

- To guarantee that the optimal solution is identified in both first-set optimisation and second-set optimisation, other evolutionary algorithms, for instance, genetic algorithm, artificial bee colony optimisation, firefly optimisation, and ant colony optimisation can be extensively explored to obtain potential better optimisation results.
- In this study, nominal thermal and electrical efficiency is assumed for each energy device. However, in practical applications, the operating efficiency may be affected by varying weather conditions and part-

Table 7
Performance comparison between the proposed retrofitting strategy and "operating carbon emissions optimisation only" retrofitting approach.

	Reference "operating carbon emissions optimisation only" retrofitting approach	Proposed retrofitting approach
Roof insulating material (m^2)	1,499	1,499
Wall insulating material (m^2)	605	605
Solar panel (m^2)	2,963	2,817
Solar heating system (m^2)	37	129
CHP system (kW)	130	100
Wind generator (kW)	203	178
Electricity storage (kWh)	474	566
Biomass boiler (kW)	0	78
Whole-life cost ($\times 10^6$ £)	6.21	5.47
Whole-life energy usage ($\times 10^8$ MJ)	2.37	2.12
Whole-life carbon emissions ($\times 10^7$ kg)	1.24	1.11
Payback year of investment cost	27.73	23.25
Payback year of embodied energy	14.08	11.53
Payback year of embodied carbon	13.22	11.25
Cost savings-to-investment	1.18	1.58
Energy reduction-to-embodied	3.31	4.20
Carbon reduction-to-embodied	3.53	4.33

load operating ratio. In the future study, the dynamic efficiency of each energy device should be adopted to represent its real situation.

- The uncertainty in weather condition and building energy behaviour can also be considered during both design optimisation and operating optimisation stages.

7. Conclusion

Drawbacks of state-of-the-art retrofitting strategies include lacking coordination the collective performance from both passive and active retrofitting measures; focusing on minimising cost, energy usage and carbon emissions only during its operating stage; adopting a fixed operating schedule for active energy devices; and using thermodynamic simulation results from archetype buildings. Therefore, the retrofitting solutions may not be able to achieve the minimum whole-life carbon emissions. In this study, an integrated passive and active retrofitting approach is proposed for transforming office buildings towards whole-life minimum carbon emissions. There are three innovative features in the proposed retrofitting approach. Through two inter-related design and operating optimisation processes, the set of retrofitting options can be identified to achieve overall optimal economic, energy, and environmental performance. The first innovation is that whole system simulation is conducted to evaluate the collective effects among a range of active and passive refurbishment measures. The active retrofitting options include biomass boiler and biomass CHP system, while the passive retrofitting options include solar panel, solar heating system and wind generator. The second innovation is that the cradle to grave life-cycle optimisation is conducted with the consideration of both embodied and end-of-life recycled carbon of various retrofitting materials and energy devices. The third innovation is that retrofitting plan at the design stage is used to iteratively determine appropriate operating schedules.

A real three-floor office building acquiring retrofitting is used to test the feasibility and effectiveness of this integrated passive and active retrofitting approach. Historical gas and electricity usage, design parameters of pre-retrofitted building, historical meteorological profiles, and life-cycle inventory information from a number of sources are employed to represent real-world situation. The retrofitting plan and operating schedules of energy system would be iteratively decided through a circular process of two sets of optimisations. It is demonstrated that once the proposed retrofitting strategy is implemented on the case study building, 44%, 74% and 68% reduction in lifelong costs, carbon emissions and energy usages can be achieved. Compared to retrofitting the building using the state-of-the-art "design optimisation only" strategy, the proposed retrofitting approach can reduce 5.36%-34.37% whole-life energy consumption and 4.31%-51.10% carbon emissions. Compared to retrofitting the building using the state-of-the-art "operating carbon emission only" strategy, there is 11.92%, 10.55%, and 10.48% reduction in whole-life cost, energy usage and carbon emissions, respectively.

CRediT authorship contribution statement

X.J. Luo: Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review & editing, Resources, Data curation, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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