Life cycle assessment approach for renewable multi-energy system: a comprehensive analysis

X.J. Luo, Lukumon O. Oyedele*, Hakeem A. Owolabi, Muhammad Bilal, Anuoluwapo O. Ajayi and Olugbenga O. Akinade

Big Data Enterprise and Artificial Intelligence Laboratory
University of the West of England, Frenchay Campus, Bristol, United Kingdom
*Corresponding author: l.oyedele@uwe.ac.uk

Abstract

In response to the gradual degradation of natural sources, there is a growing interest in adopting renewable resources for various building energy supply. In this study, a comprehensive life cycle assessment approach is proposed for a renewable multi-energy system (MES) to evaluate its primary energy consumption, economy cost and carbon emission from cradle to grave. The MES, consisting of passive side and active side, is fully driven by renewable energy including solar, wind and biomass. On the passive side, building integrated photovoltaic, solar collector and wind turbines are adopted. On the active side, the biomass-fuelled combined cooling heating and power system (CCHP) serves as the primary energy supplier. The electric compression chiller and biomass boiler are adopted when the thermal energy from the CCHP system is not sufficient, while electricity is imported from the city power grid when the electricity demand is low. A representative office building in the United Kingdom and real-life inventory data is adopted to demonstrate the effectiveness of the proposed life cycle assessment approach. Through life cycle assessment, the advantages and disadvantages of the MES are compared with the reference CCHP system and conventional separate system in view of life cycle primary energy consumption, economy cost and carbon emission. Moreover, to gain an insight into the life cycle performance, the sensitivity analysis is conducted on the rated capacity of the power generation unit, climate zones, life span, recycle ratio and interest rate. The life cycle cost of MES is relatively higher than the conventional separate system mainly owing to the high construction cost of BIPV, wind turbine, solar collector and biomass feedstock. However, its life cycle primary energy consumption and carbon emission are much lower. It is believed that the proposed life cycle assessment approach can provide useful guidelines for government in policymaking and for building engineers in retrofitting works.

Keywords: Life cycle assessment; Multi-energy system; Renewable; Biomass; Building-integrated photovoltaic; Wind turbine.

1. Introduction

In view to solve the global problem of energy shortage and environmental emission, various technologies have been implemented to develop energy-efficient and environmental-friendly building energy systems. Natural gas-driven combined cooling heating and power (CCHP) systems have been widely investigated for simultaneously, effectively and efficiently satisfying heating, cooling and electrical energy demands. Biomass, the renewable energy source, with lower primary energy consumption, economic investment and carbon emission, can also be adopted as to drive the CCHP system. Furthermore, solar collectors, building-integrated photovoltaics (BIPV) and wind turbines can additionally be applied to utilise the solar and wind energy.

1.1 Related studies

To improve the efficiency of CCHP system and multi-energy system (MES), various design and operation optimization approaches have been proposed to minimize its year-round operating primary energy consumption, operating cost and carbon emission. To determine the optimal rated and operating capacity of each energy device in the MES, Luo *et al.* [1] proposed a two-stage capacity optimization approach for the stand-alone MES. The MES was independent on city power grid; thus the optimization objective of was the year-round consumption of biomass. To determine the optimal operating capacity of a stand-alone residential MES, Luo *et al.* [2] proposed an integrated demand and supply-side management strategy for a stand-alone CCHP system serving the residential building. The demand-side rolling optimization, supply-side rolling optimization and feedback correction algorithms were adopted. The optimization objective was the year-round primary energy consumption. Luo *et al.* [3] also proposed a multi-supply-multi-demand strategy for a stand-alone CCHP system primed with solid oxide fuel cell. The optimization objective was to minimize its year-round primary energy consumption for the office building. Zhu *et al*. [4] proposed a genetic algorithm-based design optimization approach for a CCHP system to minimize its annual operating cost. Rui *et al.* [5] proposed a bi-objective optimization and multi-criteria evaluation integrated framework for a solid oxide fuel cell-driven CCHP system. The annual operating cost and carbon emission of the CCHP system was set as the optimization objective. Aritz *et al.* [6] proposed a control optimization strategy for a Stirling engine-based residential hybrid system for space heating and domestic hot water production. The bi-optimization criteria are operating cost and exergy for one week with the peak load. Kuang *et al.* [7] proposed a stochastic operation optimization for a CCHP system with energy storage. The optimization objective is the year-round operating cost. Luo *et al.* [8] proposed a multi-objective capacity optimization approach for a distributed energy system to achieve the overall coefficient of energy performance, life cycle cost and year-round operating carbon emission. Mohammadali *et al.* [9] proposed an optimal thermal and electrical operation optimization strategy for a hybrid photovoltaic-fuel cell-battery energy system. The optimization objective was the annual operating cost. Wang *et al.* [10] proposed a combined multi-objective optimization and robustness analysis framework for building integrated energy system under uncertainty. The economic optimization is based on the total of capital and operating cost, while the environmental optimization is according to the carbon emission during the operating stage. Martin *et al.* [11] proposed an environmental and economic multi-objective optimization approach for a residential hybrid renewable energy system. The economic optimization was based on the total of capital and operating cost, while the environmental optimization is according to the annual operating carbon emission. Chen *et al.* [12] proposed a planning and operation optimization approach for the energy hub to minimize its total cost of investment, operation and lifetime loss. To improve the utilization ratio and energy efficiency of distributed renewable energy sources, Wang *et al.* [13] developed a thermodynamic model for a solar assisted CCHP system based on biomass gasification. The effects of part-load-ratio of the prime mover and the solar irradiation on the system performance were investigated. To achieve the minimum life cycle cost of the MES, Wu *et al.* [14] proposed a system design optimization approach based on exhaustive search method. Namely, a cost-oriented index was defined to determine the optimal system configuration. To reduce primary energy consumption and greenhouse gas emission, Nelson *et al.* [15] proposed an optimization strategy to minimize its year-round operating energy consumption and emission of pollutants. Simultaneously considering the energy, environment and economic aspects, Liu *et al.* [16] proposed an operation strategy based on the variational electric cooling to cool load ratio to minimize its year-round operating primary energy consumption, economic cost and carbon emission. Rong *et al.* [17] proposed an optimization approach to determine the optimal capacity and operating strategy for a hybrid CCHP and ground source heat pump system. The year-round operating primary energy saving ratio, carbon emission reduction ratio and cost saving ratio were adopted as the optimization objectives, respectively. Lu *et al.* [18] proposed an optimization approach for the CCHP system, the sequence control configuration methods, the sequential quadratic programming algorithm and the feedback correction mechanism were adopted so as to achieve the minimum life cycle cost. Ju *et al.* [19] proposed a multi-objective optimization model for a renewable MES to minimize its energy rate, life cycle cost and year-round carbon dioxide emission reduction. Su *et al.* [20] conducted the performance optimization for a solar assisted CCHP system based on biogas reforming. The year-round primary energy saving, annual total cost-saving, and carbon dioxide emission reduction were evaluated.

The optimization objectivity, adopted climate, active devices, renewable energy devices and power grid connectivity is summarized in Table 1. Although various operating strategies have been proposed to determine the design and operating capacities of various equipment units within the CCHP system and MES, the optimization objectives were mainly focused on year-round primary energy consumption, greenhouse gas emission and operating cost. Although a literature mentioned the life cycle cost [8, 10, 11, 12, 14, 18, 19], the primary energy consumption and carbon emission during the construction stage was generally not considered. Life Cycle Assessment is a widely used tool to assess energetic and environmental impacts (i.e. irreversible depletion of energy sources and damages to human health, ecosystem and resources) [21] throughout the life cycle stages of a product or a process. The life cycle stages are generally from the extraction of the raw materials through production, operation, use and end-of-life [22-23]. It quantifies the primary energy consumed and carbon emission released [24]. The LCA methodology is recognized as a powerful sustainability assessment tool [25], [26] as it can prevent shifting the burden from one life cycle stage to another [27]. Therefore, when conduct building energy system design and retrofitting, the overall life cycle performance of primary energy consumption, economic cost and carbon emission should be taken into account simultaneously.

1.2 Research gaps and Contribution

Although various energetic, environmental and economic performance assessment has been conducted on the CCHP system and MES, the following research gaps were identified:

- The optimization objective was generally focused on the single year-round primary energy consumption, operating cost and carbon emission, while the meaningful amount of energy consumption, economic costs and greenhouse gas during the construction stage were generally not accounted for.
- Most of the prime movers in the existing CCHP system is fuelled by natural gas. The effects of full-set adoption of renewable energy devices on building energy demands and system management were not considered.
- The performance of biomass-fuelled CCHP system in the temperate climate, in which electrical and heating energy demands are large while cooling demand is relatively small, has not been evaluated.

To overcome the research gaps, the major contribution of this study is summarized as follows:

- A full-set renewable MES is designed, meaning that the MES is primarily rely on renewable energy during the operating stage. BIPV and solar heater are adopted to utilize solar energy, wind turbine is implemented to make use of wind energy, while the CCHP system and auxiliary boiler is fuelled by biomass.
- A life cycle assessment approach is proposed to ensure a comprehensive analysis of the renewable MES. The performance evaluation of the renewable MES at temperate climate is conducted regarding its life cycle primary energy consumption, economic cost and carbon emission. To implicate the real-life case, the local practical data is adopted as much as possible.
- A wide-ranging sensitivity analysis is conducted to investigate the affecting factors on MES life cycle performance. The sensitivity analysis covers the different rated capacities of power generation

Table 1. Summary of literature review.

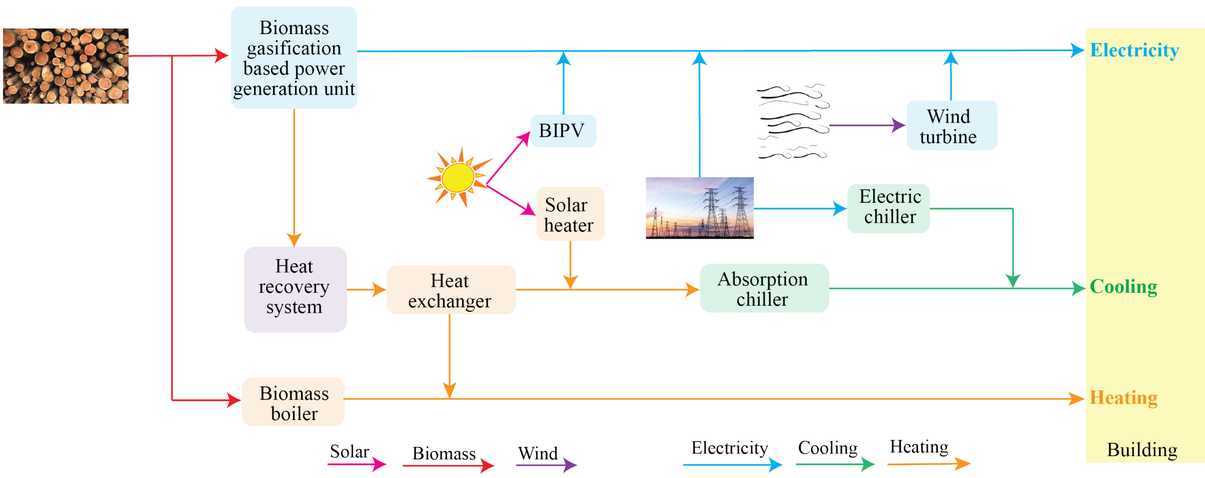
Ref.	Energy	Economy	Carbon emission	Climate	Active devices	Renewable energy devices
[1]	Year-round operating			United Kingdom	Biomass-based CCHP system	PV and solar collector
[2]	Year-round operating			Hong Kong	Fuel cell - based CCHP system	N.A.
[3]	Year-round operating			Hong Kong	Fuel cell - based CCHP system	N.A.
[4]		Year-round operating		Guangzhou	Natural gas CCHP system	
[5]		Year-round operating	Year-round operating	Beijing, Shanghai and Xiamen	Fuel cell - based CCHP system, battery	PV panel
[6]		Peak-week operating		Northern Spain	Hybrid systems for space heating and Domestic Hot Water	
[7]		Year-round operating		China	Natural gas CCHP system	PV panel, Wind power, solar hot water
[8]	Overall coefficient of energy performance	Life cycle	Year-round operating	Changsha, China	Distributed energy system	Solar collector, PV panel and ground source heat pump
[9]		Year-round operating		Iran	Fuel cell/battery hybrid energy system	PV panel
[10]		Life cycle	Year-round operating	Beijing	Natural gas CCHP system	PV panel, wind turbine
[11]		Life cycle	Year-round operating	Denmark and Spain	Heat pump and thermal energy storage	PV panel, wind power and solar collector
[12]		Life cycle		Hubei, China	Battery, power grid	PV panel
[13]	Energy efficiency				Natural gas CCHP system	Solar thermal biomass gasification
[14]		Life cycle		Weifang, China	Natural gas CCHP system	Solar collector
[15]	Year-round operating		Year-round operating	USA, TX, Fort Worth, and MN, Minneapolis	Natural gas CCHP system	
[16]	Year-round operating	Year-round operating	Year-round operating	Victoria, BC, Canada	Natural gas CCHP system	
[17]	Year-round operating	Year-round operating	Year-round operating		Natural gas CCHP system	Ground source heat pump
[18]		Life cycle		Tianjin	Natural gas CCHP system	Ground source heat pump, PV panel
[19]	Energy rate	Life cycle	Year-round operating		Natural gas CCHP system	solar panel, wind turbine
[20]	Year-round operating	Year-round operating	Year-round operating		Natural gas CCHP system	

unit, locations and climates, recycle ratio, life span and investment interest on life cycle primary energy consumption, economic cost and carbon emission.

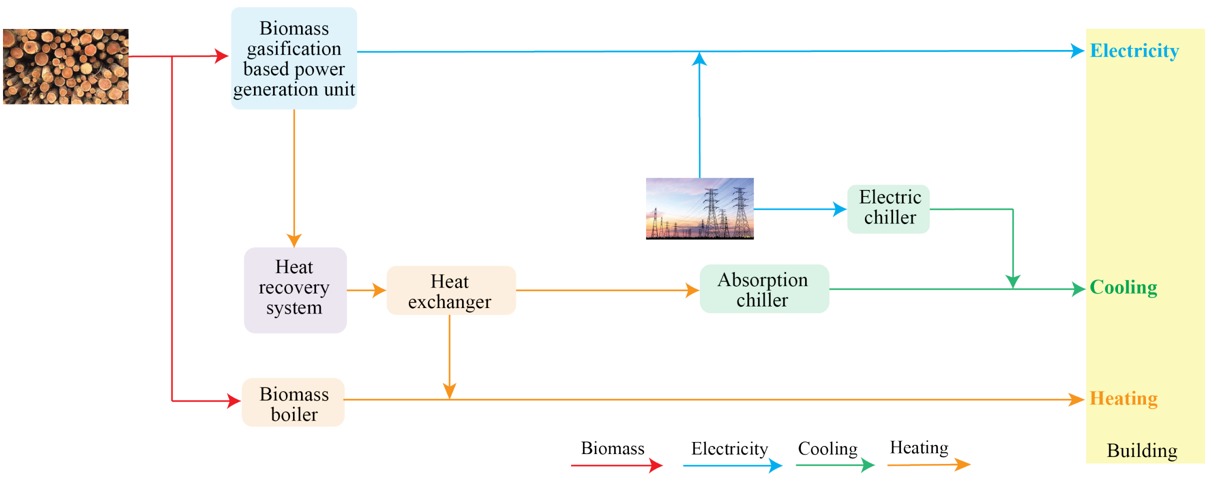
The rest of the paper is organized as follows: The next section introduces the renewable MES and building energy information; the third section illustrates the life cycle assessment approach; the fourth section discusses the life cycle assessment results; the fifth section details the implication for practice and future direction while the last section draws the conclusion.

2. The renewable multi-energy system and building energy information

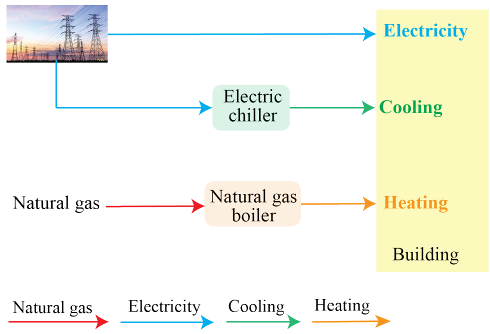
In order to evaluate the life-cycle performance of the proposed renewable MES, a reference CCHP system and a conventional separate system are adopted for comparison purposes.



(a) MES



(b) CCHP system



(c) Conventional separate system

Fig. 1. Schematic diagram of the three energy systems.

2.1 *The renewable multi-energy system*

The schematic diagram of the renewable multi-energy system is illustrated in Fig. 1, along with the CCHP system and conventional separate system. The MES consists of the passive side and the active side.

- The passive side mainly includes BIPV, wind turbine and solar heater. At the operating stage, the thermal output from the solar collector as well as the electricity output from the BIPV and wind turbine are sole depended on the weather data (i.e. outdoor air dry-bulb temperature, relative humidity, global solar radiation and wind speed).
- At the active side, the biomass gasification driven power generation unit, along with the heat recovery system and absorption chiller, serves as the key role for simultaneously providing heating, cooling and electrical energy. The electric compression chiller and the biomass boiler are operated when the power generation unit and its bottoming side is not sufficient to satisfy the building cooling and heating demands, respectively.

The CCHP system only includes the active side of the MES. In other words, the BIPV, solar heater, and wind turbine is not involved. The conventional separate system consists of a natural gas-driven boiler for heating, an electric compression chiller for cooling, while the electricity is imported from the city power grid.

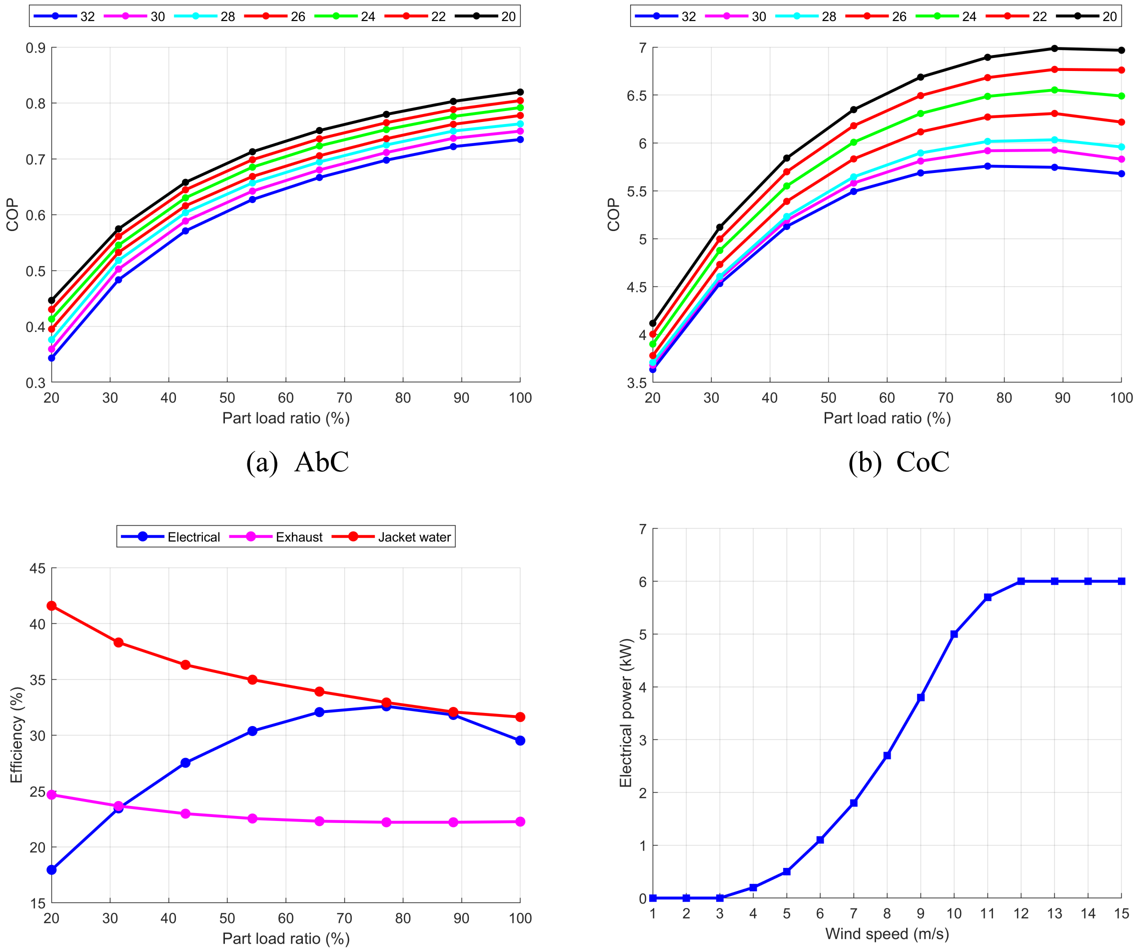
The thermodynamic models of each energy device in the renewable MES are summarized in Table 2. To ensure the system energetic performance close to the real-world situation, the effects of the outdoor environment and loading conditions on the electrical efficiency of BIPV, wind turbine, power generation unit, the thermal efficiency of power generation unit as well as the coefficient of performance (COP) of absorption chiller (AbC) and electric compression chiller (CoC) are accounted. The electrical and thermal efficiency of the PGU is shown in Fig. 2 (a). Meanwhile, the COP of AbC and CoC are dependent on cooling water inlet temperature and the part-load ratio, as shown in Fig. 2 (b) and (c). The design parameters of each energy device are summarized in Table 3.

Table 2. Thermodynamic model of the MES.

BIPV [23]	$Q_{BIPV} = \varphi A_{BIPV}\eta_{BIPV}$ $\eta_{BIPV} = \eta_{BIPV,n}[1 + \varepsilon_T(T_{DB} - T_{ref})][1 + \varepsilon_\varphi(\varphi - \varphi_{ref})]$
Wind turbine	See Fig. 2(d)
Solar heater [24]	$Q_{SH} = \varphi A_{SH}\eta_{SH}$ $\eta_{SH} = \eta_{SH,n} - \alpha \times (T_{DB} - T_{SH})/\varphi$
Biomass gasifier [22]	$Q_{BG} = m_{bio,PGU}LHV_{bio}\eta_{BG}$
Power generation unit [25]	$Q_{PGU,e} = \eta_{PGU,e}Q_{BG}$ $Q_{PGU,jw} = (5.1396 \cdot e^{-0.02619 \cdot PLR} + 11.346 \cdot e^{0.001194 \cdot PLR})Q_{BG}$ $Q_{PGU,exh} = (3.4264 \cdot e^{-0.02619 \cdot PLR} + 7.564 \cdot e^{0.001194 \cdot PLR})Q_{BG}$
Heat recovery system [25]	$Q_{PGU,h} = (Q_{PGU,jw} + Q_{PGU,exh}) \times \eta_{rec}$
Absorption chiller [26]	$Q_{AbC} = Q_{AbC,h}COP_{AbC}$, see Fig. 2(a)
Electric compression chiller [26]	$Q_{CoC} = Q_{CoC,e}COP_{CoC}$, see Fig. 2(b)
Biomass boiler [22]	$Q_B = \eta_B m_{bio,B}LHV_{bio}$

Table 3. Design parameters of energy devices.

	Design parameter	Value
BIPV [27]	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
Solar heater [24]	Nominal efficiency $\eta_{SC,n}$ (%)	44
Heat recovery system [25]	Efficiency η_{rec} (%)	90
Biomass boiler [25]	Efficiency (%)	70
Natural gas boiler [2]	Efficiency (%)	70



(a) AbC (b) CoC

(c) PGU (d) Wind turbine

Fig. 2. Performance curve of AbC, CoC, PGU and wind turbine.

2.2 Building information

To evaluate the life cycle performance of the MES, the reference CCHP system and the conventional separate system, a representative 4-storey office building in the United Kingdom as detailed in the design guideline [28, 29] is adopted as the reference building. The detailed information, including the floor plan, occupant, lighting, office equipment, cooling/heating set-point, indoor design condition, as well as the thermal property of building envelops of the reference building can be found in [1]. Since outdoor air dry-bulb temperature, relative humidity, solar radiation and wind speed have different effects on the heating, cooling and electricity demand of the building as well as the operating performance of each equipment unit in the MES. The methodology in determining the design capacity of different equipment units in the MES is also introduced in this section.

2.2.1 Weather data in different locations

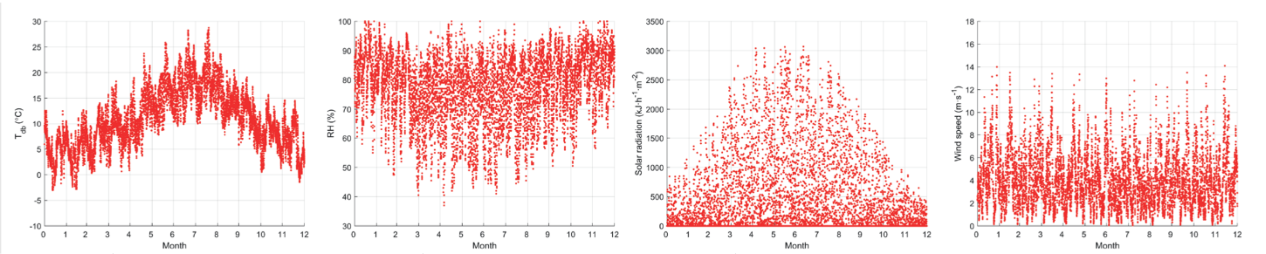
To evaluate the life cycle performance of the proposed renewable MES under different climate conditions, 5 different locations in the United Kingdom are investigated. The 5 locations include the south-east city London, the south-costal city Efford, the central coastal city Cardiff, the West Midlands city Birmingham and the north-east city Aberdeen. London, Cardiff and Birmingham have temperate oceanic, essential maritime and temperate maritime climate, respectively, while both Efford and Aberdeen has oceanic climate. The dry-bulb temperature, relative humidity, solar radiation and wind speed during the typical meteorological year are adopted, as depicted in Fig. 3, while a brief comparison is summarized in Table 4.

The year-round trend of dry-bulb temperature, relative humidity, solar radiation and wind speed are similar among the five locations, but their maximum, minimum, average and annual-total values are different in various cities.

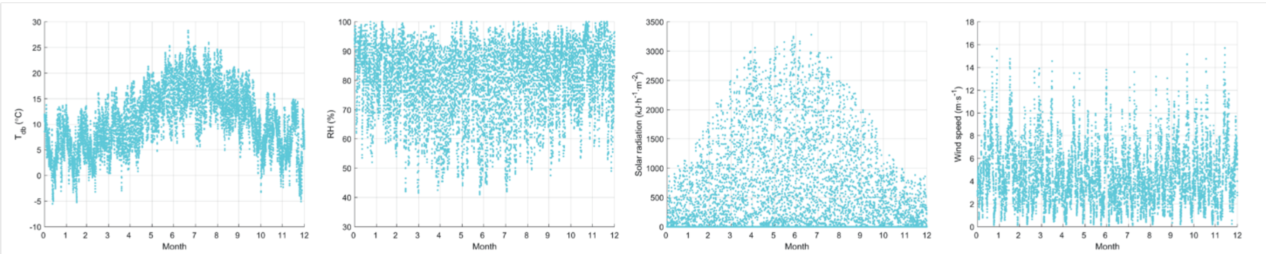
- The outdoor air dry-bulb temperature reaches about 24~29 °C in summer, while drops to around -3 ~ -7 °C in winter. London has the highest peak and average outdoor air dry-bulb air temperature, while Birmingham has the lowest dry-bulb air temperature in winter.
- The relative humidity varies from 35% to 100% during the year. Birmingham has the lowest minimum while the highest average relative humidity. Meanwhile, London has the lowest average relative humidity.
- As the south-costal city, Efford has the largest peak and total solar radiation, with the value of 3280 $kJ{\cdot}h^{-1}\ m^{-2}$ and 3952 $MJ{\cdot}\ m^{-2}$. London and Aberdeen have the lowest peak and total value of solar radiation, respectively.
- As the inland city, London has the lowest peak and average wind speed. On the contrary, as the coastal city, Cardiff has the largest peak and average wind speed, followed by Aberdeen and Efford.

Table 4. Brief comparison of the five different climate zones.

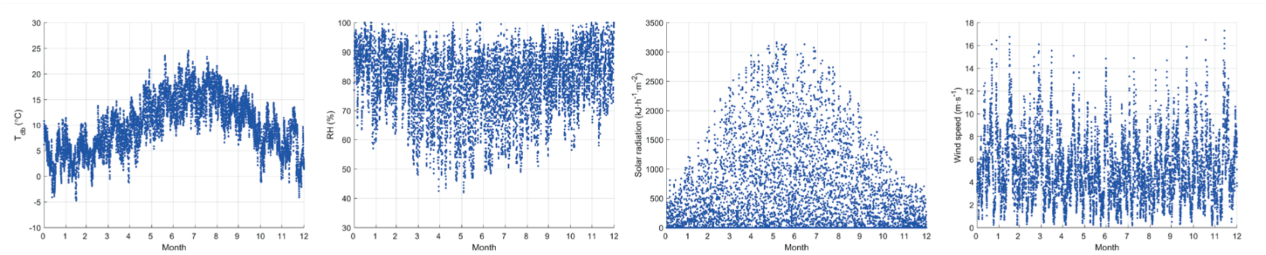
Weather data	Feature	London	Efford	Cardiff	Birmingham	Aberdeen
Dry-bulb temperature	Maximum (°C)	28.8	28.3	24.6	28.5	24.0
	Minimum (°C)	-3	-5.6	-4.8	-7.3	-7.1
	Average (°C)	10.8	10.7	9.8	9.0	7.8
Relative humidity	Maximum (%)	100	100	100	100	100
	Minimum (%)	37	41	42	35	42
	Average (%)	77	79	79	82	81
Global solar radiation	Peak ($kJ{\cdot}h^{-1}\ m^{-2}$)	3070	3280	3167	3195	3107
	Total ($MJ{\cdot}\ m^{-2}$)	3323	3952	3533	3246	3116
Wind speed	Maximum ($m{\cdot}s^{-1}$)	14.1	15.7	17.3	15.1	16.3
	Average ($m{\cdot}s^{-1}$)	4.0	4.6	5.2	4.3	4.8



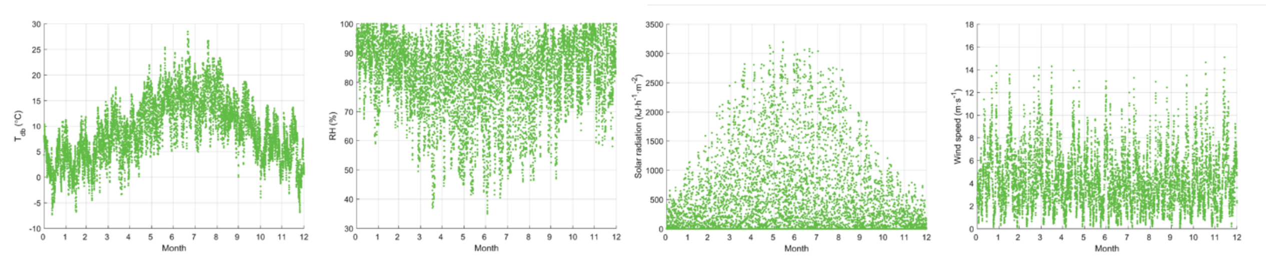
London



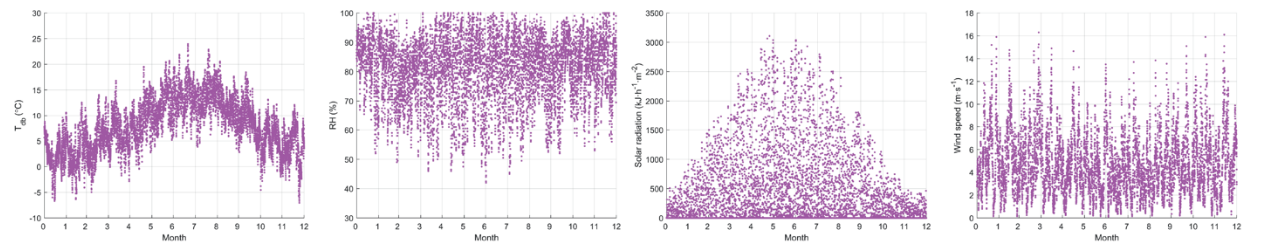
Efford



Cardiff



Birmingham



Aberdeen

Fig. 3. Weather data in different cities.

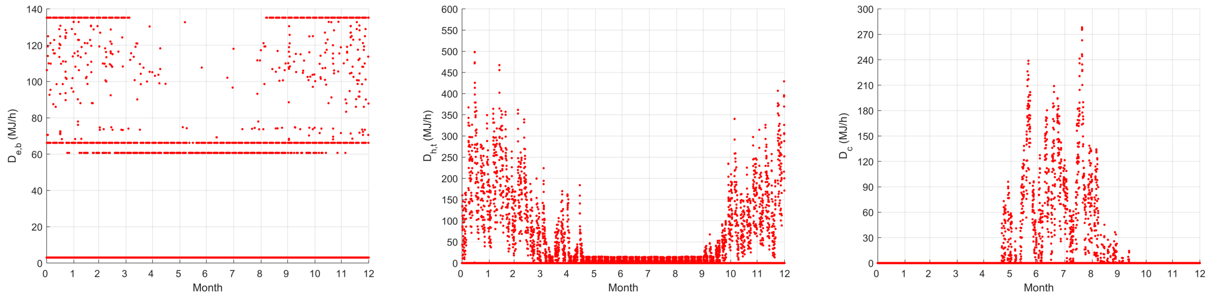
2.2.2 Building energy demands and renewable energy production

Through the validated TRNSYS simulation model developed in [1], the heating, cooling and electrical energy demands of the office building in different locations can be determined, as shown in Fig. 4.

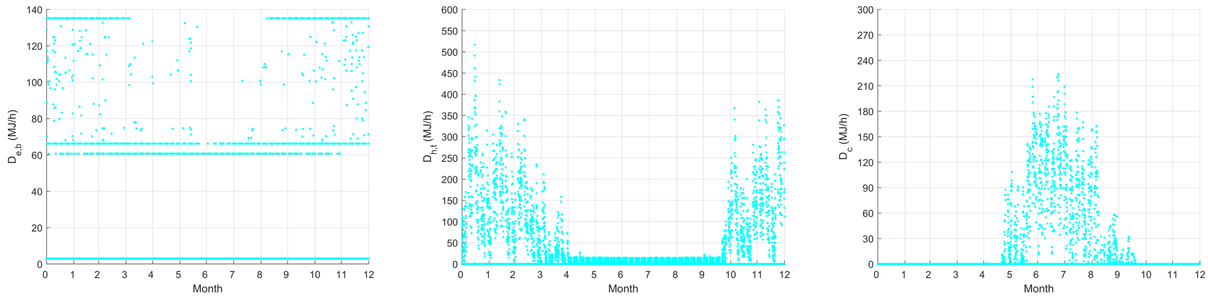
Meanwhile, the thermal energy production from the solar collector, as well as the electricity output from BIPV and wind turbine, can also be obtained, as shown in Fig. 5. The peak and total cooling, heating and electrical energy demands of the office building are summarized in Table 5. The peak and total heat production from the solar collector, along with the electricity production from the BIPV and wind turbine, are summarized in Table 6.

When BIPV is implemented, the heating and cooling demand are lower than those when BIPV is not implemented. Since the electricity demand is only used for lighting and office equipment, the peak electricity demand D_e is the same among different climate zones.

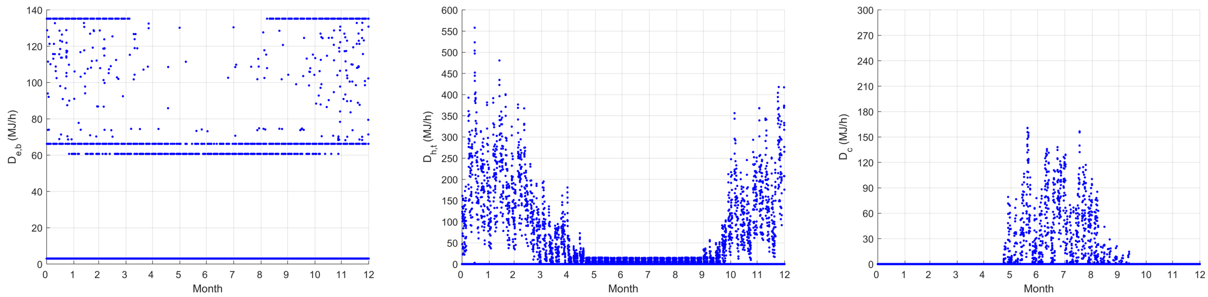
- London has the lowest peak heating demand, highest peak cooling demand and lowest wind power production due to its lowest dry-bulb temperature, highest average relative humidity, and lowest wind speed.
- Efford has the lowest total heating demand, highest total cooling demand, highest electricity production from BIPV and thermal energy production from the solar collector due to its highest peak and total solar radiation.
- Cardiff has the highest total wind power production due to its highest wind speed.
- Birmingham has the average value of heating demand, cooling demand, electricity production and thermal production.
- Aberdeen has the highest peak and total heating demand as well as the lowest peak and total cooling demand due to its lowest solar radiation and second-lowest minimum outdoor air dry-bulb temperature.



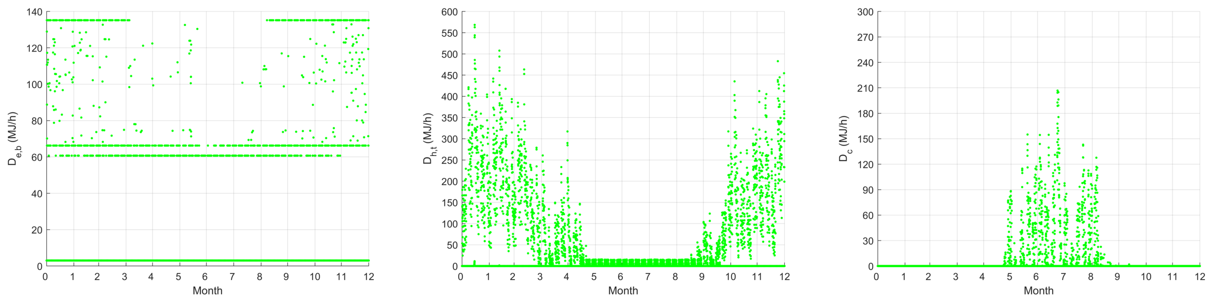
(a) London



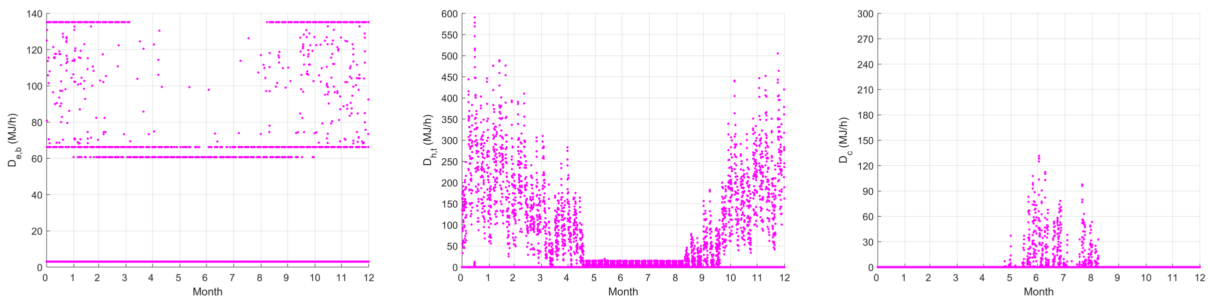
(b) Efford



(c) Cardiff

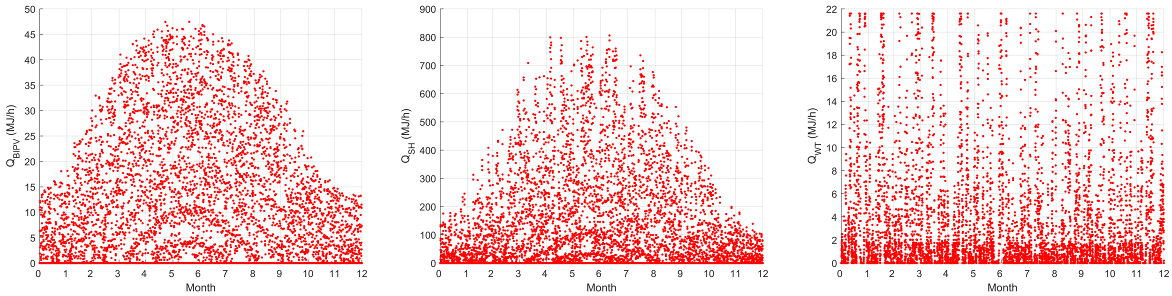


(d) Birmingham

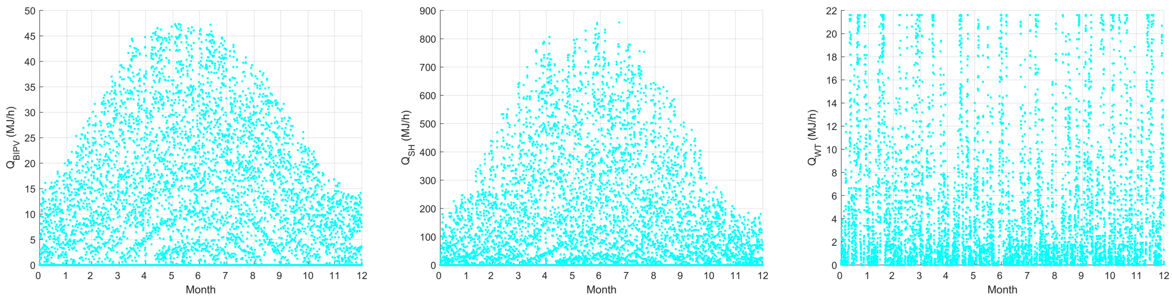


(e) Aberdeen

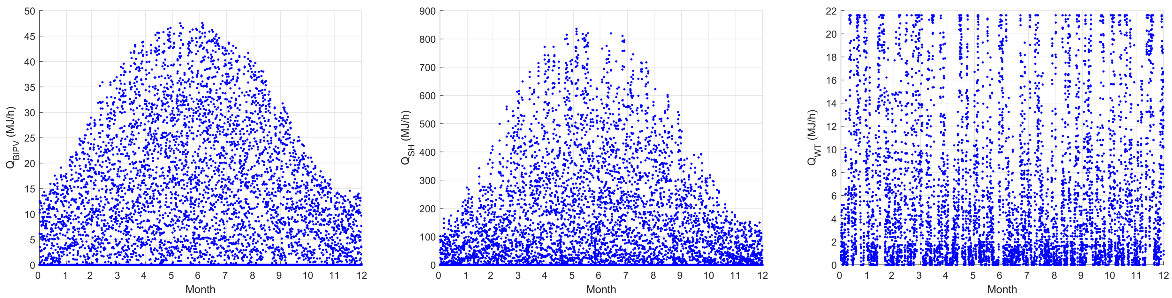
Fig. 4. Heating, cooling and electrical energy demands in different locations.



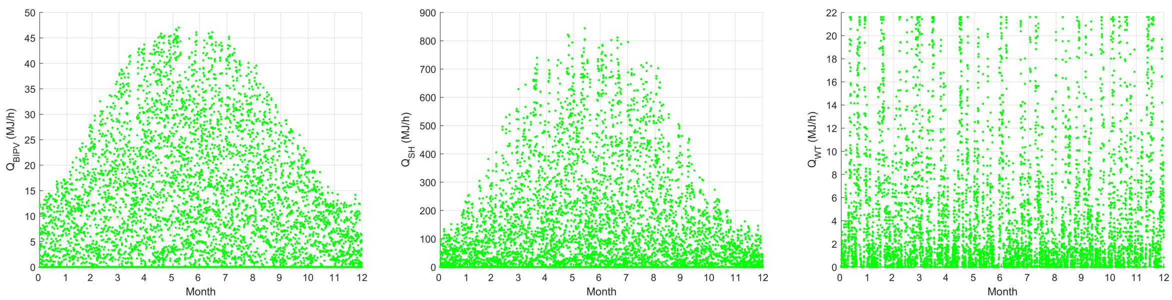
(a) London



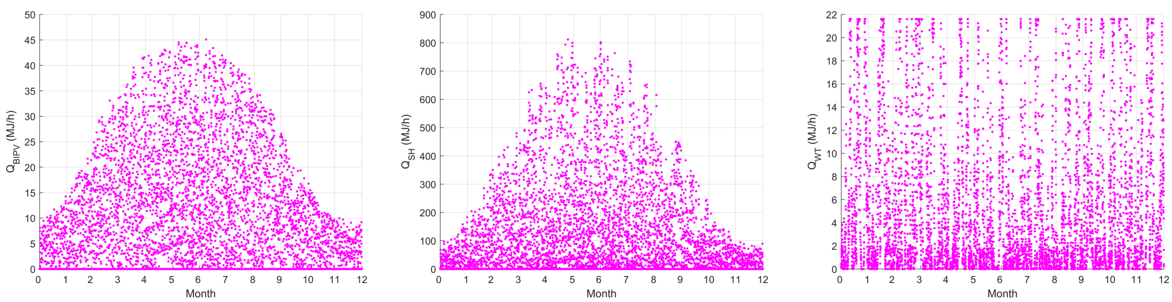
(b) Efford



(c) Cardiff



(d) Birmingham



(e) Aberdeen

Fig. 5. Electrical and thermal energy production from renewable energy devices in different locations.

Table 5. Energy demands in different locations.

Climate zone	BIPV installed or not	Peak heating demand (MJ/h)	Total heating demand (GJ)	Peak cooling demand (MJ/h)	Total cooling demand (GJ)	Peak electricity demand (MJ/h)	Total electricity demand (GJ)
London	No	524.4	240.0	375.6	141.6	135	255
	Yes	498.0	234.0	278.4	72.0		255
Efford	No	542.4	216.0	318.0	159.6		250
	Yes	517.2	212.4	224.4	76.8		250
Cardiff	No	583.2	258.0	243.6	106.8		253
	Yes	558.0	253.2	160.8	40.8		253
Birmingham	No	598.8	307.2	298.8	94.8		256
	Yes	567.6	300.0	206.4	37.2		256
Aberdeen	No	621.6	342.0	237.6	57.6		261
	Yes	590.4	333.6	132.0	13.2		261

Table 6. Energy production from the passive side of MES.

	London	Efford	Cardiff	Birmingham	Aberdeen
Peak BIPV electricity production (MJ/h)	47.5	47.4	47.6	47.0	45.1
Total BIPV electricity production (GJ)	69.7	73.4	71.6	66.6	62.5
Peak WT electricity production (MJ/h)	21.6				
Total WT electricity production (GJ)	29.4	39.3	51.5	34.6	43.7
Peak solar collector heat production (MJ/h)	806	858	836	844	812
Total solar collector heat production (GJ)	819	974	870	800	761

2.2.3 Determination of rated capacity

On the passive side, BIPV and solar heater is installed on the south wall and roof of the office building, with the area of 224 m^2 and 350 m^2, respectively. The nominal capacity of the wind turbine is 6 kW. To evaluate the effects of rated PGU capacity on the life cycle performance of MES, different rated PGU capacity, in the range of 30 - 135 kJ/h is tested. The rated capacity of biomass gasification system, heat recovery system, absorption chiller, and electrical compression chiller is determined according to the corresponding rated PGU capacity in each case.

- The rated capacity of biomass gasification system is determined to ensure there is sufficient biomass gasification capability to drive the PGU when it is at full-load operation;
- The rated capacity of heat recovery system is determined to guarantee that the thermal energy from exhaust gas and jacket water of the PGU can be fully utilized;
- The rated capacity of absorption chiller is determined so as the recovered thermal energy from heat recovery system can be fully utilised to fuel the chiller when both works at full load.
- The rated capacity of electrical compression chiller is determined to ensure that the cooling demand can be satisfied by working together with absorption chiller.

2.3 System control strategy

To determine the operating capacity of energy devices in the active side of MES, the modified following electricity load strategy is adopted. The operating capacity of PGU is first determined according to electricity demand, after which the electricity importation rate from the city power grid is determined. Next, the operating capacity of biomass boiler, absorption chiller, electric compression chiller and the additional electricity importation rate is determined according to the heating demand D_h and cooling demand D_c. The flow of the modified following electricity load strategy is illustrated in Fig. 6.

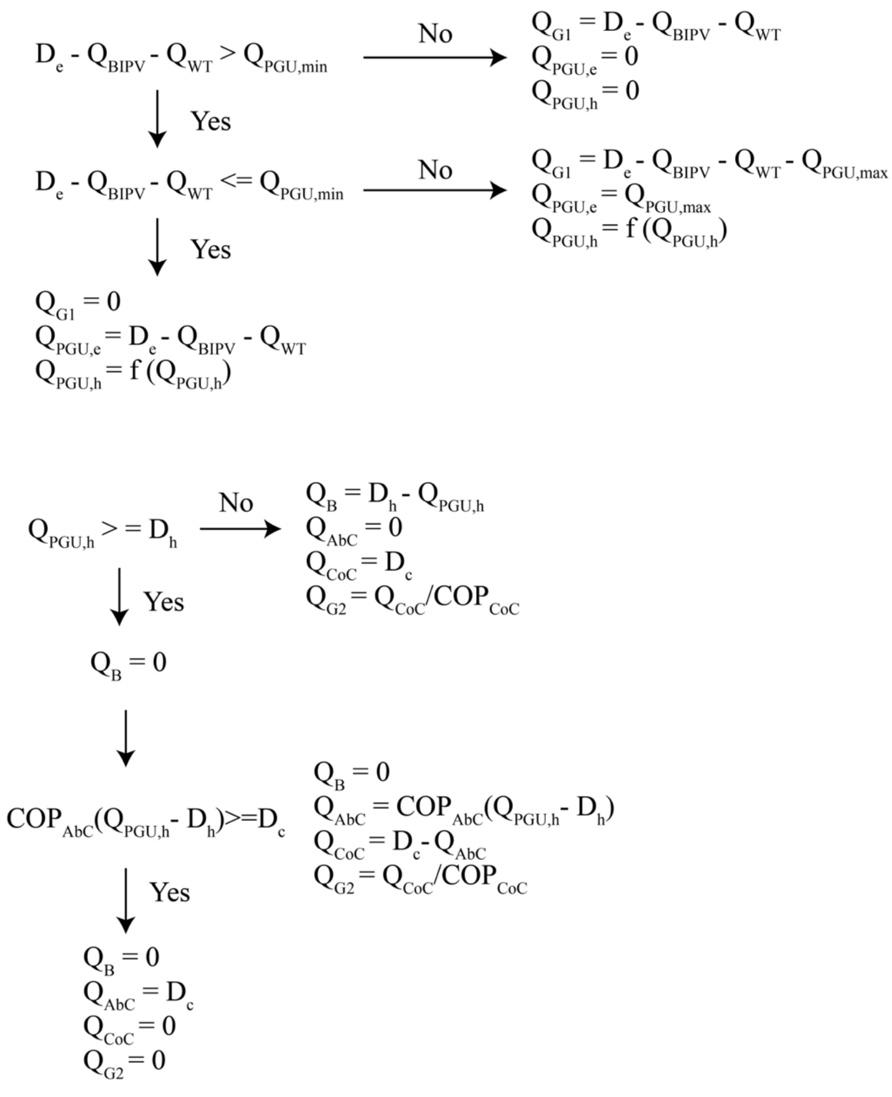


Fig. 6. Flow of the modified following electricity load strategy.

Therefore, the electricity importation rate and biomass consumption rate can be determined as:

$$Q_G = Q_{G1} + Q_{G2} \tag{1}$$

$$m_{bio} = \frac{Q_{PGU,e}}{\eta_{PGU}\eta_{BG}LHV_{bio}} + \frac{Q_B}{\eta_B LHV_{bio}} \tag{2}$$

3. **Life cycle assessment approach**

To evaluate the life cycle performance of the proposed renewable MES, the reference CCHP and conventional separate system, their life-long primary energy consumption, economic cost and carbon emission is assessed. The life cycle information data are chosen according to the real-case in the United Kingdom.

3.1 Life cycle analysis of MES

The life cycle impacts of the MES are mainly caused by biomass consumption, electricity importation from the city grid as well as the construction of energy devices. The annual primary energy consumption, economic cost and carbon emission equals to the sum of corresponding elements for biomass consumption, electricity importation and energy device construction:

$$PEC_{MES} = \sum_{h=1}^{h=8760} m_{bio} \cdot PEC_{bio} + \sum_{h=1}^{h=8760} q_e \cdot PEC_e + CRF_{PEC} \cdot \sum C_{ed,i} \cdot PEC_{ed,i} \quad (3)$$

$$COST_{MES} = \sum_{h=1}^{h=8760} m_{bio} \cdot COST_{bio} + \sum_{h=1}^{h=8760} q_e \cdot COST_e + CRF_{COST} \cdot \sum C_{ed,i} \cdot COST_{ed,i} \quad (4)$$

$$CE_{MES} = \sum_{h=1}^{h=8760} m_{bio} \cdot CE_{bio} + \sum_{h=1}^{h=8760} q_e \cdot CE_e + CRF_{CE} \cdot \sum C_{ed,i} \cdot CE_{ed,i} \quad (5)$$

where

m_{bio}: total consumption rate of biomass feedstock from biomass PGU and boiler (kg/h)

q_e: electricity importation rate (kJ/h)

$C_{ed,i}$: rated capacity of the i^{th} energy device

CRF: capital recovery factor, and

$$CRF_{PEC} = \frac{1}{ls} \quad (6)$$

$$CRF_{COST} = \frac{I \cdot (1+I)^{ls}}{(1+I)^{ls} - 1} \quad (7)$$

$$CRF_{CE} = \frac{1}{ls} \quad (8)$$

$$PEC_{equip,i} = (1 - r_{rec}) \cdot PEC_{con,i} \quad (9)$$

$$COST_{equip,i} = [1 - (1 - r_{sal})^{ls}] \cdot COST_{con,i} \quad (10)$$

$$CE_{equip,i} = (1 - r_{rec}) \cdot CE_{con,i} \quad (11)$$

where

I: the interest rate, which is in the range of 6-8 [40]

ls: life span, which is in the range of 15-20.

$PEC_{con,i}$: PEC during the construction of the i^{th} equipment

$COST_{con,i}$: economic cost during the construction of the i^{th} equipment

$CE_{con,i}$: CE during the construction of the i^{th} equipment

r_{rec}: recycle ratio, which is in the range of 50%-90%

r_{sal}: economic recycle ratio with annual salvage value ratio, and $r_{sal} = 5\%$

The constructive parameters of various energy devices in the passive and active sides of MES are summarized in Tables 7 and 8, respectively. The life cycle information of the biomass feedstock is summarized in Table 9, while the information of electricity from the city power grid is summarized in Table 10.

Table 7. Life cycle information of the passive energy system.

BIPV [30, 31]		Wind turbine [32, 33]		Solar heater [34]	
PEC (MJ/m^2)	3266.6	*PEC* (GJ)	3334	*PEC* (GJ/m^2)	3
COST (£/m^2)	310	*COST* (£)	498300	*COST* (£/m^2)	38
CE (kg/ m^2)	157.8	*CE* (kg)	20926	*CE* (kg/m^2)	240

Table 8. Life cycle information of the biomass gasification based CCHP system [22, 35].

	PEC (MJ/kW)	*COST* (£)	*CE* (kg/kW)
Biomass gasifier	1927.8	$294\ C_{BG}$	278.8
ICE generator	559.629	$800\ C_{PGU}$	80.934
Biomass boiler	85.05	$44\ C_B$	12.3
Heat recovery system	107.73	$23.5C_{rec}$	15.58
Absorption chiller	1041.579	$470.88 \times C_{AbC}^{0.872}$	150.634
Electric compression chiller	231.336	$(420 \times C_{CoC}^{-0.07273} - 139) \times C_{CoC}$	33.456

Table 9. Life cycle information of biomass feedstock [36-38].

	Total
PEC_{bio} (kJ/kg)	1593
$COST_{bio}$ (£/kg)	0.26
CE_{bio} (kg/kWh)	0.01563

Table 10(a). Life cycle information of electricity [37].

PEC_e (kWh/kWh)	2.5
CE_e (kg/kWh)	0.59

Table 10(b). Life cycle information of electricity [39].

$COST_e$	London	Efford	Cardiff	Birmingham	Aberdeen
Operating (£/kWh)	0.1453	0.1468	0.1507	0.1425	0.1397
Standing (£/day)	0.2039	0.1925	0.2030	0.2054	0.2147

3.2 LCA for CCHP system

The life cycle impacts of the CCHP system consist of impacts caused by the usage of biomass, the electricity importation from the power grid and the construction of each equipment unit in the CCHP system.

$$PEC_{CCHP} = m_{bio} \cdot PEC_{bio} + q_e \cdot PEC_e + CRF_{PEC} \cdot \sum C_{ed} \cdot PEC_{ed,i} \tag{12}$$

$$COST_{CCHP} = m_{bio} \cdot COST_{bio} + q_e \cdot COST_e + CRF_{COST} \cdot \sum C_{ed} \cdot COST_{ed,i} \tag{13}$$

$$CE_{CCHP} = m_{bio} \cdot CE_{bio} + q_e \cdot CE_e + CRF_{CE} \cdot \sum C_{ed} \cdot CE_{ed,i} \tag{14}$$

3.3 LCA for conventional separate system

The life cycle impacts of the conventional separate system consist of impacts caused by the usage of natural gas, the electricity importation from the power grid and the construction of natural gas-fired boiler. The information regarding natural gas is summarized in Table 11.

$$PEC_{SS} = m_{ng} \cdot PEC_{ng} + q_e \cdot PEC_e + CRF_{SS} \cdot (C_B \cdot PEC_B + C_{CoC} \cdot PEC_{CoC}) \tag{15}$$

$$COST_{SS} = m_{ng} \cdot COST_{ng} + q_e \cdot COST_e + CRF_{SS} \cdot (C_B \cdot COST_B + C_{CoC} \cdot COST_{CoC}) \tag{16}$$

$$CE_{SS} = m_{ng} \cdot CE_{ng} + q_e \cdot CE_e + CRF_{SS} \cdot (C_B \cdot CE_B + C_{CoC} \cdot CE_{CoC}) \tag{17}$$

Table 11. LCA information of natural gas [37, 41].

PEC_{ng} (MJ/kWh)	3.6
$COST_{ng}$ (£/kWh)	0.028
CE_{ng} (kg/kWh)	0.18385

3.4 Affecting factors of life cycle performance

The key affecting factors considered in this study include rated capacity of biomass PGU, recycle ratio of materials for energy devices, life span of energy devices, as well as interest rate in the region area.

- As discussed in Section 2.1, biomass PGU is the major prime mover for the CCHP system, thus its rated capacity has a significant effect on life cycle performance of the MES. When rated capacity of PGU is low, more thermal and electrical energy need to be generated from biomass boiler and imported from power grid, respectively. To make sensible sensitivity analysis, the maximum rated capacity of PGU is set to be equal to the maximum electricity demand (135 MJ/h, according to Table 5). Therefore, the rated capacity of PGU is tested in the range of 30-135 MJ/h.
- Material recycle is an effective approach in preventing solid waste from entering the landfill. From the life cycle point of view, the more materials can be recycled, the lower quantities of raw material inputs for multi-energy system is required for the extraction and processing of these materials [42]. There is a large variation of recycle ratio among different types of materials. The recycle ratio of bulk materials and copper can reach 95%, while the recycle ratio of plastics, concrete and strategic metals is 0 [43-44]. Therefore, the material recycle ratio is tested in the range of 50%-90%.

- During the operating stage of each energy device, there exists performance degradation and the operating efficiency would be decreased after certain life span. There also exists large variation of life span among different energy devices. For example, the life span for electric compression chillers, wind turbine, PV panels, biomass gasification system and is 15, 15, 20 and 25 years, respectively [45, 46]. Longer lifespan would result in less equivalent annual primary energy consumption and carbon emission. Therefore, the material recycle ratio is tested in the range of 15-20 years.
- The interest rate is adopted to compare revenue and expenditure that occur at different points of time. It is variable along different time period, and it is dependent on the regional economy of a certain country. According to [40], the interest rate is 6-8% in developed countries. Therefore, the interest rate is tested in the range of 6-8% in this study.

4. Results and discussion

Following electricity load strategy was implemented on both the MES and CCHP systems. For the conventional separate system, the electricity importation rate is determined by the actual cooling and electrical energy demand, while the operating capacity of the natural gas fired boiler is influenced by the actual heating demand.

4.1 Performance evaluation of MES

To study how the energy supplies of both the MES and CCHP system matched with the actual cooling, heating and electricity demands in each hour throughout a day, operating capacity contribution from the corresponding equipment units for cooling, heating and electricity supplies are shown in Figs. 7. The hottest day in each city is chosen to present the cooling supply contribution, while the coldest day is selected to illustrate the heating supply contribution.

For heating energy supply:

- In the CCHP system, the exhaust heat recovered from the PGU formulates the basis of heating production energy, while the operating capacity of the biomass boiler is determined by the actual heating demand and the operating capacity of PGU.
- In the MES system, both the exhaust heat recovered from the PGU and the thermal energy from solar collector make up the basis of heating energy, while the operating capacity of the biomass boiler is determined by the actual heating demand, the operating capacity of PGU and the solar radiation.

For electrical energy supply:

- In the CCHP system, the electricity demand is mainly satisfied by the PGU. When the electricity demand is below 10% of the design capacity of PGU or higher than the rated capacity of PGU, electricity is imported from the city power grid.
- In the MES, wind turbine and BIPV are first adopted to provide electrical energy since there is no PEC, economy cost and CE during operating stage. The electrical power from BIPV and wind turbine are determined by solar radiation and wind speed, respectively. Due to the adoption of BIPV and wind turbine, the operating capacity of PGU and the electricity importing rate from city power grid can be decreased. During the off-peak hours, when the electricity demand is relatively low, there will be surplus electricity production from wind turbine and BIPV.

For cooling energy supply:
In both the CCHP system and MES, the absorption chiller and the electric compression chiller can work together to satisfy the actual cooling demand at any time on each day. The operating capacity of the absorption chiller depends on the operating capacity of PGU, while the operating capacity of the electric compression chiller is determined by the actual cooling demand and the operating capacity of absorption chiller.

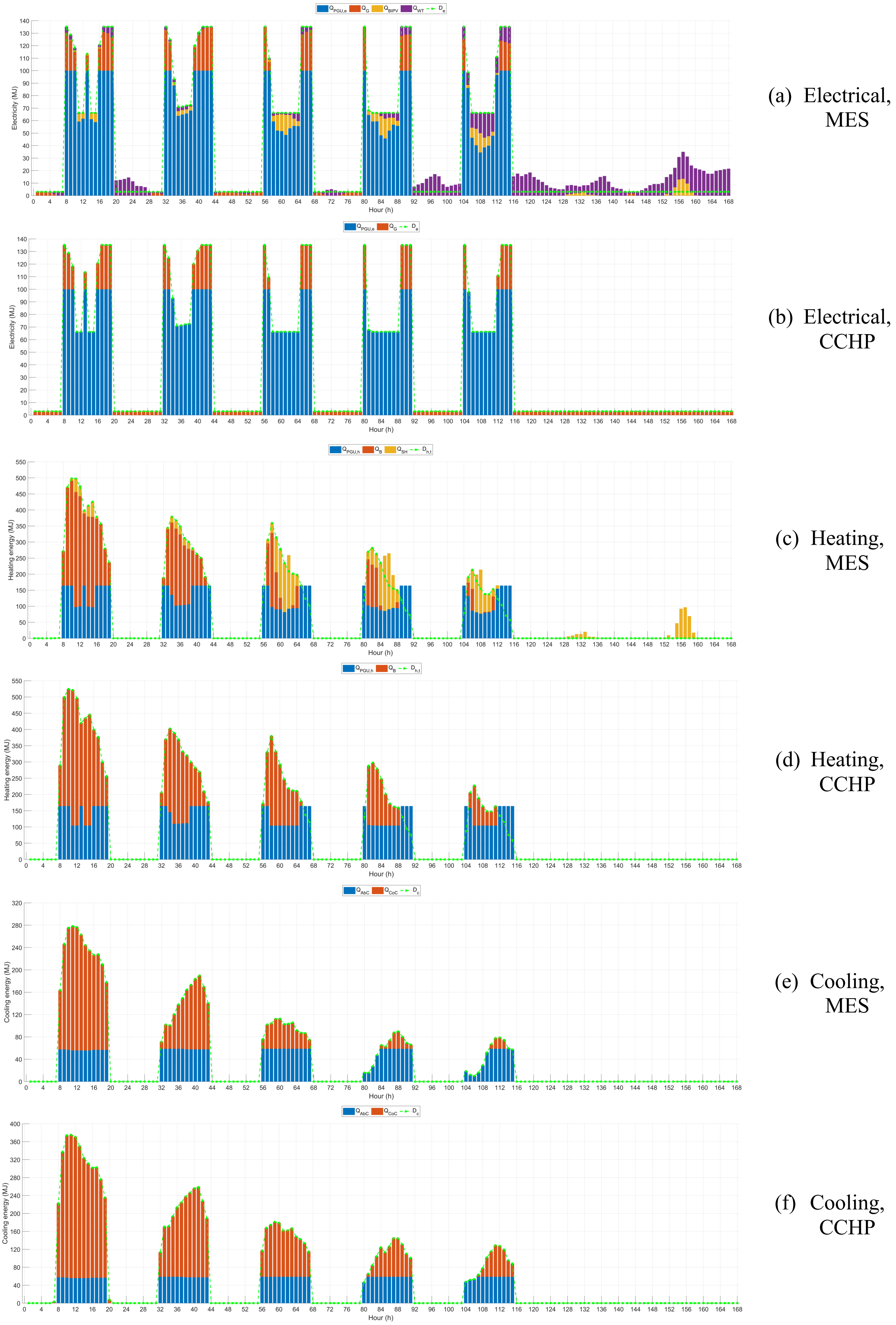


Fig. 7. Electrical, heating and cooling contribution from different energy devices.

4.2 *Life cycle assessment*

To evaluate the performance of the renewable MES, its life cycle primary energy consumption (PEC), economic cost (COST) and carbon emission (CE) is compared with the reference conventional separate system and CCHP system, respectively. To compare the life cycle PEC, COST and CE of MES, CCHP system and conventional separate system, the corresponding values of life cycle PEC, COST and CE when rated capacity of PGU C_{PGU} = 50 MJ/h, interest rate I = 0.08, life span ls = 20 and recycle ratio r_{rec} = 90% are summarised in Table 12. The life cycle PEC of MES has the 9.4 % - 12.5 % and 12.9 % - 16.9 % reduction compared to conventional separate system and CCHP system, respectively. The life cycle CE of MES has the 78.8 % - 80.7 % and 20.9 % - 25.5 % reduction compared to conventional separate system and CCHP system, respectively. However, the life cycle economy cost of MES has the 47.3 % - 57.0 % and 10.5 % - 16.4 % increase compared to conventional separate system and CCHP system, respectively.

Table 12. Life cycle analysis of CCHP system and MES.

		London	Efford	Birmingham	Cardiff	Aberdeen
PEC	Conventional separate system (× 10^8 kJ)	1101	1052	1190	1103	1242
	CCHP system (× 10^8 kJ)	1146	1108	1230	1161	1276
	MES (× GJ)	998	940	1057	965	1095
	MES compared to separate system (%)	9.4	10.6	11.2	12.5	11.8
	MES compared to CCHP system (%)	12.9	15.2	14.1	16.9	14.2
COST		London	Efford	Birmingham	Cardiff	Aberdeen
	Conventional separate system (×10^4 £)	15.1	14.7	15.1	15.0	15.1
	CCHP system (× 10^4 £)	19.5	18.9	20.5	20.0	21.0
	MES (× 10^4 £)	22.7	21.7	23.4	22.1	23.7
	MES compared to separate system (%)	50.3	47.6	55.0	47.3	57.0
	MES compared to CCHP system (%)	16.4	14.8	14.1	10.5	12.9
CE		London	Efford	Birmingham	Cardiff	Aberdeen
	Conventional separate system (× ton)	39.6	37.3	44.4	40.2	47.1
	CCHP system (× 10^6 kg)	10.7	10.2	11.0	10.6	11.5
	MES (× 10^6 kg)	8.2	7.9	8.7	7.9	9.1
	MES compared to separate system (%)	79.3	78.8	80.4	80.3	80.7
	MES compared to CCHP system (%)	23.4	22.5	20.9	25.5	20.9

4.2.1 Comparison of life cycle PEC, COST and CE among the three energy systems

MES needs the smallest PEC owing to its effective utilization of renewable energy by BIPV, wind turbine and solar collector. Take London as an example, according to Table 6, there are 70 GJ electrical energy production from BIPV, 29 GJ electrical power production from wind turbine and 819 GJ thermal energy production from solar collector. If the produced electrical and thermal energy is fully utilized, according to Table 10 and 11, it equals to 174 + 74 GJ and 942 GJ PEC by city power grid and natural gas boiler, respectively. Moreover, the energy utilization ratio of MES is higher than that of city power grid and natural gas boiler. To be more specific, according to Table 2, when consuming 1kg biomass, 4.49 MJ electrical and 6.12 MJ thermal energy can be produced through PGU. According to Tables 3, 10 and 11, if the same amount of electrical and thermal energy is generated by city power grid and natural gas boiler, the PEC is 11.24 MJ + 7.035 MJ, which is about 10 times higher than the PEC of 1 kg biomass (i.e. 1.593 MJ, according to Table 9). The PEC of CCHP system is a little higher than that of the separate system. It might be caused by the inefficient operation of the CCHP system. The CCHP system is operated based on conventional following electricity mode strategy, which may result in thermal energy waste when electricity demand is high while thermal energy demand is low.

MES needs the largest COST, mainly owing to the high construction cost of renewable energy devices. Take London as an example, the 70 GJ electrical energy production from BIPV, 29 GJ electrical power production from wind turbine and 819 GJ thermal energy production from solar collector equals to £ 2813 + 1187 + 538 economy cost by city power grid and natural gas boiler (according to Table 10 and 11), respectively. However, it is much lower than the construction cost of those renewable energy devices (i.e. £ 69440 for BIPV, £ 49830 for wind turbine and £ 14875 for solar collector, according to Table 8). Moreover, the 4.49 MJ electrical and 6.12 MJ thermal energy from PGU by consuming 1kg biomass, equals to £ 0.156 from city power grid and £ 0.048 from natural gas boiler, respectively. However, according to Table 9, the cost of 1 kg biomass is £ 0.26, which is larger than £ 0.156 + £ 0.048.

The CE from MES is lower than that of the reference CCHP system, while both of them are much lower than that from the reference separate system. There are two primary reasons behind this phenomenon: the effective utilization of renewable energy devices and efficient operation of CCHP system. Take London as an example, the 70 + 29 GJ electrical energy production and 819 GJ thermal energy production from renewable energy devices equals to 11423 + 4818 kg and 1715 kg CE by city power grid and natural gas boiler, respectively. Meanwhile, when consuming 1kg biomass, 4.49 MJ electrical and 6.12 MJ thermal energy can be produced through PGU. If the same amount of electrical and thermal energy is generated by city power grid and natural gas boiler, the CE is 0.737 kg + 0.355 kg, which is about 20 times higher than the CE of 1 kg biomass (i.e. 0.056 kg).

To further evaluate the life cycle performance of the renewable energy devices, the annual electrical energy production from BIPV and wind turbine, as well as the annual thermal energy from solar collector, is summarized in Table 13. The equivalent PEC, COST and CE by generating electricity at city power grid and by generating heating energy through natural gas is also obtained.

Table 13. Life cycle assessment of renewable energy devices.

City	London	Efford	Cardiff	Birmingham	Aberdeen
BIPV power production (GJ)	70	73	72	67	63
Equivalent PEC by electricity (GJ)	174	184	179	167	156
Equivalent COST by electricity (£)	2813	2993	2997	2636	2425
Equivalent CE by electricity (kg)	11423	12029	11734	10915	10243
Wind turbine power production (GJ)	29	39	52	35	44
Equivalent PEC by electricity (GJ)	74	98	129	87	109
Equivalent COST by electricity (£)	1187	1603	2156	1370	1696
Equivalent CE by electricity (kg)	4818	6441	8440	5671	7162
Solar collector thermal production (GJ)	819	974	870	800	761
Equivalent PEC by NG boiler (GJ)	942	1120	1001	920	875
Equivalent COST by NG boiler (£)	538	567	553	514	483
Equivalent CE by NG boiler (kg)	1715	2293	3004	2018	2549

4.2.2 Comparison of life cycle performance among different cities

The composition of life cycle PEC, COST and CE in different cities are summarized in Fig. 11.

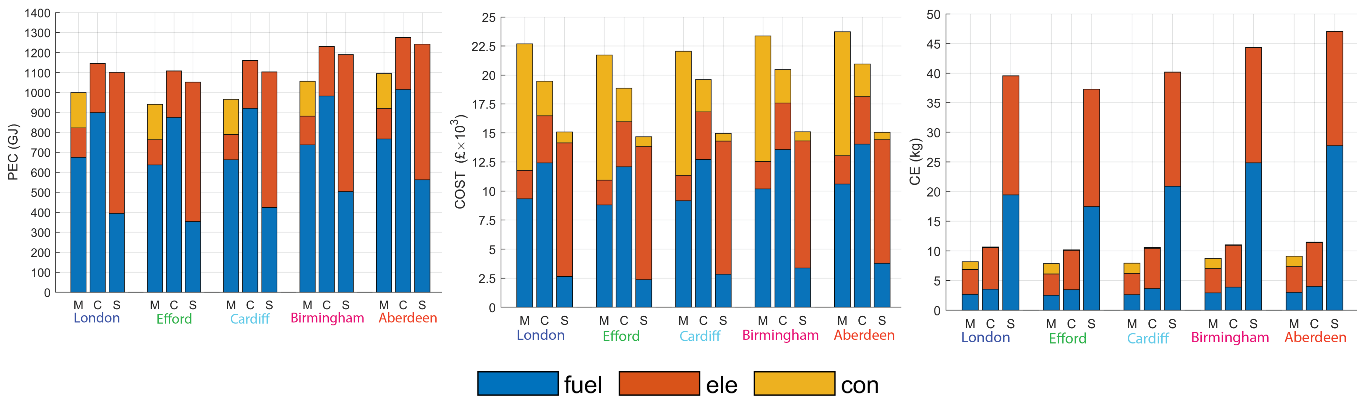


Fig. 11. Life cycle PEC, COST and CE at different locations.

For MES, the reference CCHP system and reference conventional separate system, Efford has the lowest PEC while Aberdeen results in the largest PEC in each system. It is because that Efford has the smallest building heating and electricity demand, along with the largest electricity production from BIPV and the largest thermal energy production from solar collector, as identified from Table 5 and 6. On the contrary, Aberdeen has the largest heating and electricity demand, along with the smallest electricity production from BIPV and the smallest thermal energy production from solar collector.

For MES, the reference CCHP system and reference conventional separate system, Efford and Aberdeen results in the lowest and highest economy cost in each system, respectively. For MES, the reference CCHP system and reference conventional separate system, Efford has the lowest CE while

Aberdeen results in the largest CE in each system, respectively. This is aligned with the characteristics identified in PEC and economy cost.

4.2.3 Comparison of portion of PEC, COST and CE

In MES, the largest portion of PEC is caused by biomass consumption, followed by construction of devices and electricity consumption. Due to the electricity production from BIPV and wind turbine as well as thermal energy production from solar collector, the PEC by biomass and electricity consumption in MES can be lower than that from the CCHP system, respectively. However, the PEC by constructing renewable energy devices is relatively higher than conventional energy devices.

In MES, the largest portion of COST is caused by construction of renewable energy devices, followed by biomass consumption and electricity consumption. Due to the electrical energy generation from BIPV and wind turbine, the operating cost of electricity in the MES is much lower than that of the reference CCHP system and conventional separate system. Meanwhile, due to the high unit cost of biomass, the operating fuel cost in MES is much higher than that in the conventional separate system.

In MES, the largest portion of CE is caused by importing electricity from city power grid, followed by biomass consumption and construction of energy devices. Moreover, the CE generated by importing electricity and consuming biomass is much lower than that from the conventional separate system. It is due to the clean energy generation from BIPV, solar collector and wind turbine. It also demonstrates the decarbonization ability of renewable MES.

4.3 Sensitivity analysis

The sensitivity analysis is conducted on the affecting factors, including rated PGU capacity, recycle ratio of materials, life span of energy devices and interest rate, respectively.

4.3.1 Sensitivity analysis of rated capacity of biomass PGU

Higher rated capacity of biomass PGU indicates that more electrical and thermal energy is generated by the PGU, while less electricity is imported from city power grid and less heating energy is produced by natural gas boiler. Different rated PGU capacity is adopted to evaluate its effects on life cycle PEC, COST and CE. As shown in Figs. 8-10, the life cycle PEC, COST and CE is evaluated at different rated PGU capacity, while recycle ratio, life span and interest rate is kept constant at 90%, 20 years and 8%, respectively. The life cycle performance of both MES and the reference CCHP system is also summarized in Table 14.

Table 14. Summary of sensitivity analysis regarding rated capacity of PGU.

PEC	When C_{PGU} increased from 40 MJ/h to 135 MJ/h	Biomass	MES	↑47.87%-60.67%.
			CCHP	↑44.46%-56.97%.
		Electricity	MES	↓89.67%-92.40%
			CCHP	↓86.30%-87.37%
		Construction	MES	↑0.46%-0.47%
			CCHP	↑116.59%-121.19%
		Life cycle	MES	↑14.86-22.07%
			CCHP	↑8.80-15.18%
	MES	Aberdeen > Birmingham > London > Cardiff > Efford		
	CCHP	Aberdeen > Birmingham > Cardiff > London > Efford		
	MES	Electricity > Construction > Biomass when C_{pgu} = 50 MJ/h Biomass > Construction > Electricity when C_{pgu} = 135 MJ/h		
	CCHP	Electricity > Biomass > Construction when C_{pgu} = 50 MJ/h Biomass > Electricity > Construction when C_{pgu} = 50 MJ/h		
	PEC of the reference CCHP system constantly higher than that of MES.			
COST	When C_{PGU} increased from 40 MJ/h to 135 MJ/h	Biomass	MES	↑56.19%-67.61%.
			CCHP	↑44.46%-56.97%.
		Electricity	MES	↓111.57%-116.41%
			CCHP	↓85.12%-86.09%
		Construction	MES	↑28.45%-29.24%
			CCHP	↑101.78%-109.95%
		Life cycle	MES	↑20.16-24.94%
			CCHP	↑18.34-23.72%
	MES	Aberdeen > Birmingham > London > Cardiff > Efford		
	CCHP	Aberdeen > Birmingham > London > Cardiff > Efford		
	MES	Construction > Biomass > Electricity when C_{pgu} = 50 MJ/h Biomass > Construction > Electricity when C_{pgu} = 135 MJ/h		
	CCHP	Biomass > Electricity > Construction when C_{pgu} = 50 MJ/h Biomass > Construction > Electricity when C_{pgu} = 135 MJ/h		
	COST of the reference CCHP system constantly lower than that of MES.			
CE	When C_{PGU} increased from 40 MJ/h to 135 MJ/h	Biomass	MES	↑53.91%-67.61%
			CCHP	↑34.08%-46.22%
		Electricity	MES	↓97.76%-97.89%
			CCHP	↓114.27%-119.56%
		Construction	MES	↑7.52%-9.90%
			CCHP	↑128.66%-133.74%
		Life cycle	MES	↓43.94-60.48%
			CCHP	↓59.84%-60.53%
	MES	Aberdeen > Birmingham > London > Cardiff > Efford		
	CCHP	Aberdeen > Birmingham > London > Cardiff > Efford		
	MES	Electricity > Biomass > Construction when C_{pgu} = 50 MJ/h Biomass > Construction > Electricity when C_{pgu} = 135 MJ/h		
	CCHP	Electricity > Biomass > Construction when C_{pgu} = 50 MJ/h Biomass > Electricity > Construction when C_{pgu} = 135 MJ/h		
	CE of the reference CCHP system constantly higher than that of MES.			

For both MES and the reference CCHP system, the lowest PEC is identified when the rated electrical capacity of biomass PGU is 40 MJ/h. When the rated capacity of biomass PGU is larger than 40 MJ/h, the life cycle PEC of MES increases with the increase of rated PGU capacity. At higher rated PGU capacity, the PEC of importing electricity is lower while the PEC of biomass consumption is higher. The increasing rate of PEC for biomass consumption is larger than the decreasing rate of PEC for importing electricity. For each city and each rated capacity of biomass PGU, the life cycle PEC of MES is higher than that of the corresponding reference CCHP system. The difference of PEC between MES and the reference CCHP system is lower at higher PGU rated capacity.

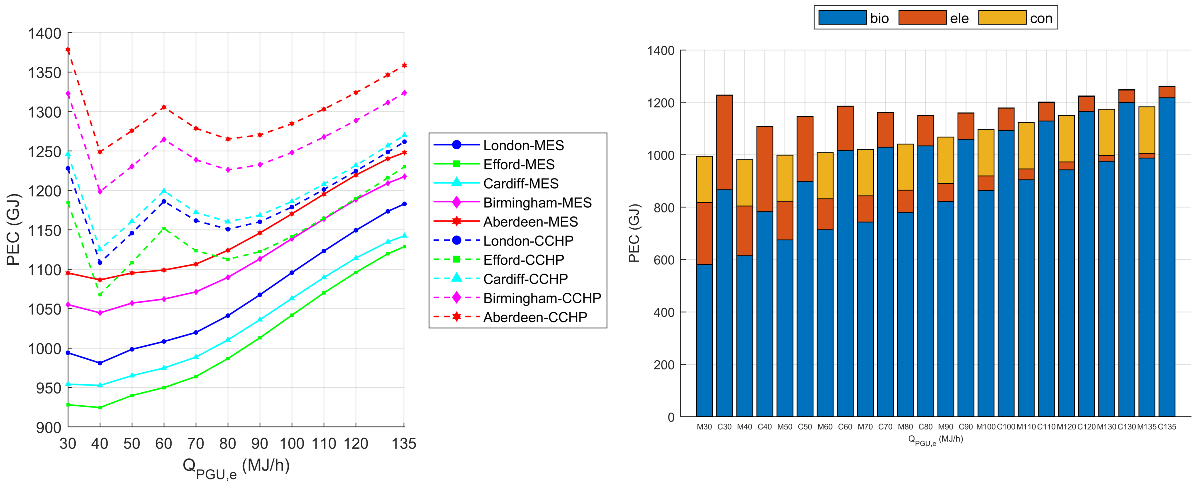


Fig. 8. Life cycle PEC at different rated capacity of PGU.

For MES and CCHP system, the lowest life cycle cost is identified when the rated capacity of biomass PGU is 30 MJ/h and 40 MJ/h, respectively. When the rated capacity of PGU is larger than 40 MJ/h, the life cycle cost of MES increases with the increase of PGU capacity. At higher rated PGU capacity, the operating cost of importing electricity from power gird is lower while the operating cost for biomass consumption and construction cost of energy devices is higher. The increasing rate of operating cost for biomass consumption and construction cost of energy devices is larger than the decreasing rate of operating cost for importing electricity. For each city and each rated capacity of biomass PGU, the life cycle cost of MES is constantly higher than that of the corresponding reference CCHP system. The difference of life cycle cost between MES and the reference CCHP system is higher at higher PGU rated capacity.

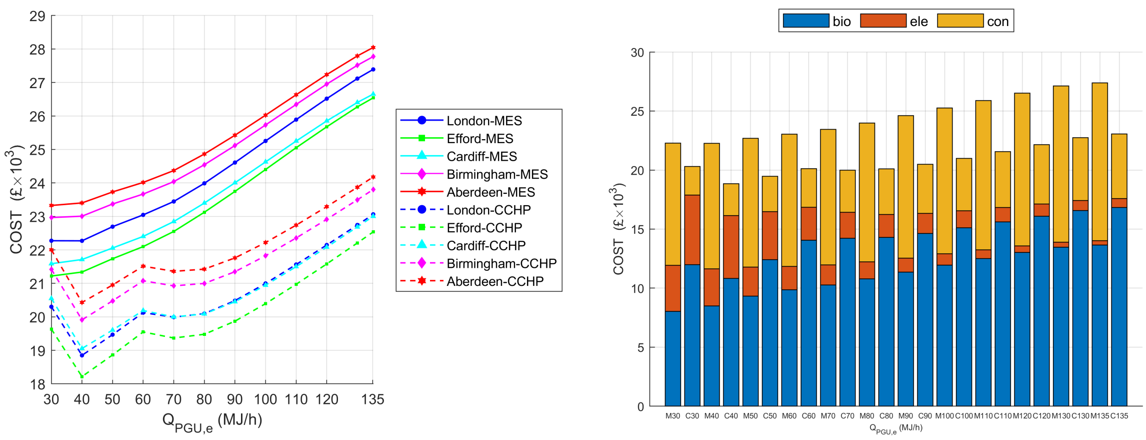


Fig. 9. Life cycle COST at different rated capacity of PGU.

For both MES and CCHP system, the lowest life cycle CE is identified when the rated capacity of biomass PGU equals to the peak electricity demand (i.e. 135 MJ/h). The life cycle CE of MES and CCHP system increases with the decrease of PGU capacity. At higher rated PGU capacity, the CE of importing electricity is lower while the CE of biomass consumption and construction of energy devices is higher. The increasing rate of CE for biomass consumption and construction of energy devices is smaller than the decreasing rate of CE for importing electricity. For each city and each rated capacity of biomass-PGU, the life cycle CE of MES is lower than that of the corresponding CCHP system. The difference of CE between MES and CCHP is lower at higher PGU rated capacity.

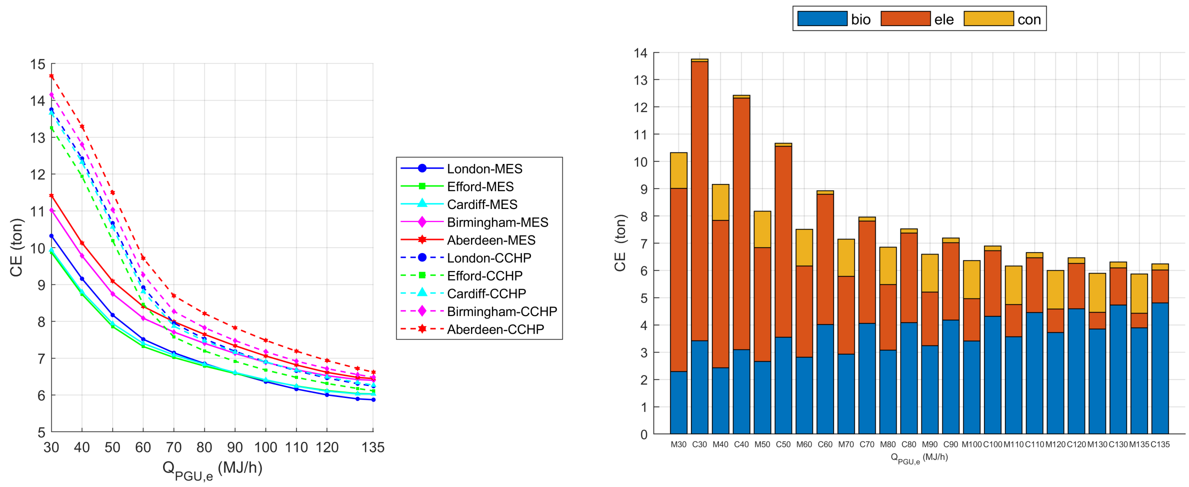


Fig. 10. Life cycle CE at different rated capacity of PGU.

4.3.2 Sensitivity analysis of recycle ratio

The composition of life cycle PEC and CE of the MES in London at different recycle ratio are summarized in Fig. 12. The rated capacity of PGU, life span and interest rate are kept constant at 50MJ/h, 20 years and 8%, respectively. The life cycle performance of primary energy consumption and carbon emission of both MES and the reference CCHP system is also summarized in Table 15.

The recycle ratio plays a big role on PEC and CE during construction stage, while has little effect on biomass and electricity consumption. According to Eq. 9, when R_{rec} decreased from 90% to 50%, the PEC and CE for construction is 4 times higher. Therefore, the life cycle PEC and CE of both MES and CCHP system increases with the decrease of recycle ratio. According to Table 15, the PEC and CE of MES construction is much larger than that of CCHP. Thus, the increasing rate of PEC and CE of MES is much larger than that of CCHP system. With higher recycle ratio, more PEC can be recovered at the end of life span. When recycle ratio is higher than 80%, the life cycle PEC and CE of MES is higher than that of CCHP system.

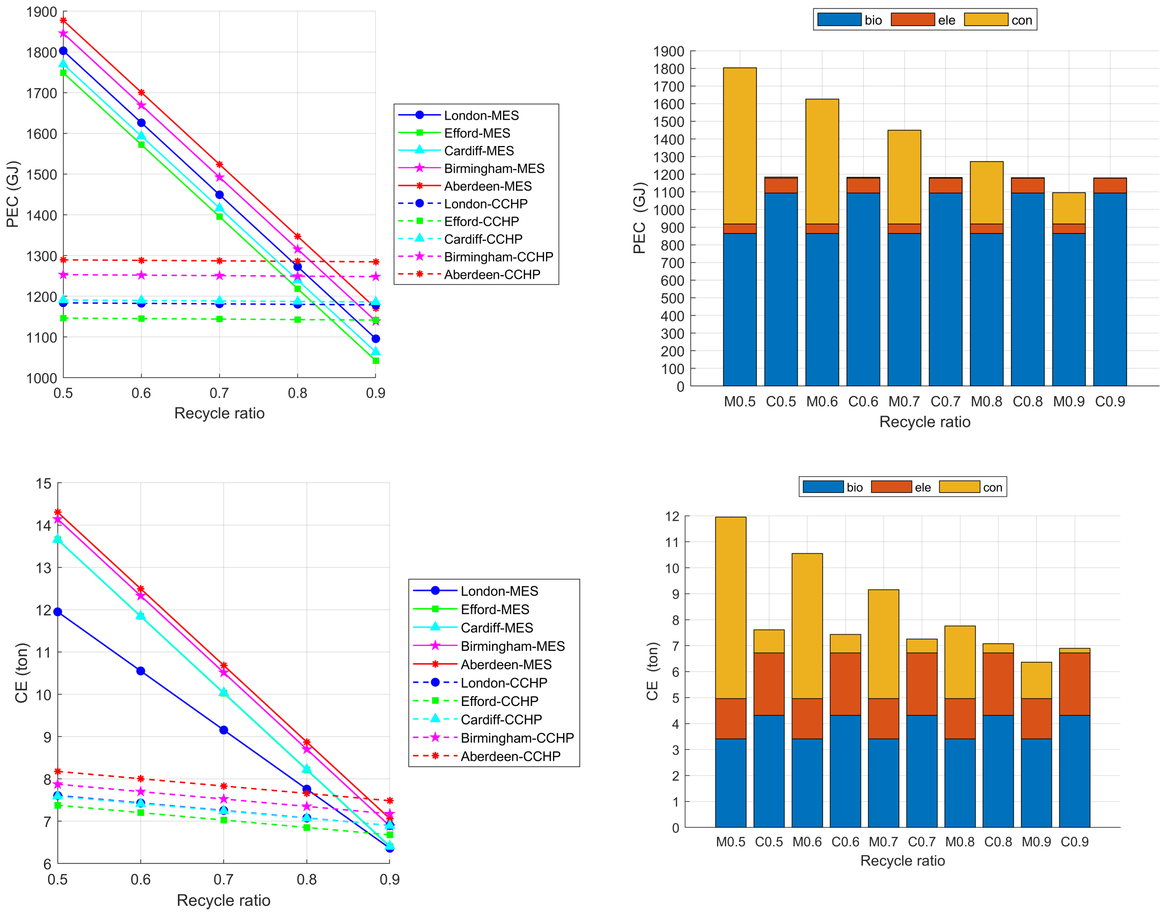


Fig. 12. Life cycle PEC and CE at different recycle ratio.

Table 15. Summary of sensitivity analysis regarding recycle ratio.

<table>
<tr><td rowspan="9">PEC</td><td rowspan="4">When R_{rec} decreased from 90% to 50%</td><td rowspan="2">Construction</td><td>MES</td><td>↑4% (according to Eq. 9)</td></tr>
<tr><td>CCHP</td><td>↑4% (according to Eq. 9)</td></tr>
<tr><td rowspan="2">Life cycle</td><td>MES</td><td>↑0.37-0.42%</td></tr>
<tr><td>CCHP</td><td>↑60.42-67.88%</td></tr>
<tr><td>MES</td><td colspan="3">Aberdeen > Birmingham > London > Cardiff > Efford</td></tr>
<tr><td>CCHP</td><td colspan="3">Aberdeen > Birmingham > Cardiff > London > Efford</td></tr>
<tr><td>MES</td><td colspan="3">Biomass > Construction > Electricity</td></tr>
<tr><td>CCHP</td><td colspan="3">Biomass > Electricity > Construction</td></tr>
<tr><td colspan="4">PEC of CCHP higher than that of MES only when R_{rec} > 80%</td></tr>
<tr><td rowspan="9">CE</td><td rowspan="4">When R_{rec} decreased from 90% to 50%</td><td rowspan="2">Construction</td><td>MES</td><td>↑4% (according to Eq. 11)</td></tr>
<tr><td>CCHP</td><td>↑4% (according to Eq. 11)</td></tr>
<tr><td rowspan="2">Life cycle</td><td>MES</td><td>↑60.42-67.88%</td></tr>
<tr><td>CCHP</td><td>↑7.50%-7.98%</td></tr>
<tr><td>MES</td><td colspan="3">Aberdeen > Birmingham > Cardiff = Efford > London</td></tr>
<tr><td>CCHP</td><td colspan="3">Aberdeen > Birmingham > London = Cardiff > Efford</td></tr>
<tr><td>MES</td><td colspan="3">Biomass > Construction > Electricity</td></tr>
<tr><td>CCHP</td><td colspan="3">Biomass > Electricity > Construction</td></tr>
<tr><td colspan="4">CE of CCHP higher than that of MES only when R_{rec} > 80%</td></tr>
</table>

4.3.3 Sensitivity analysis of life span

The composition of life cycle PEC, COST and CE of the MES in London at different life span are summarized in Fig. 13. The rated capacity of PGU, recycle ratio and interest rate are kept constant at 50MJ/h, 90% and 8%, respectively. The life cycle performance of primary energy consumption, economic cost and carbon emission of both MES and the reference CCHP system is also summarized in Table 16.

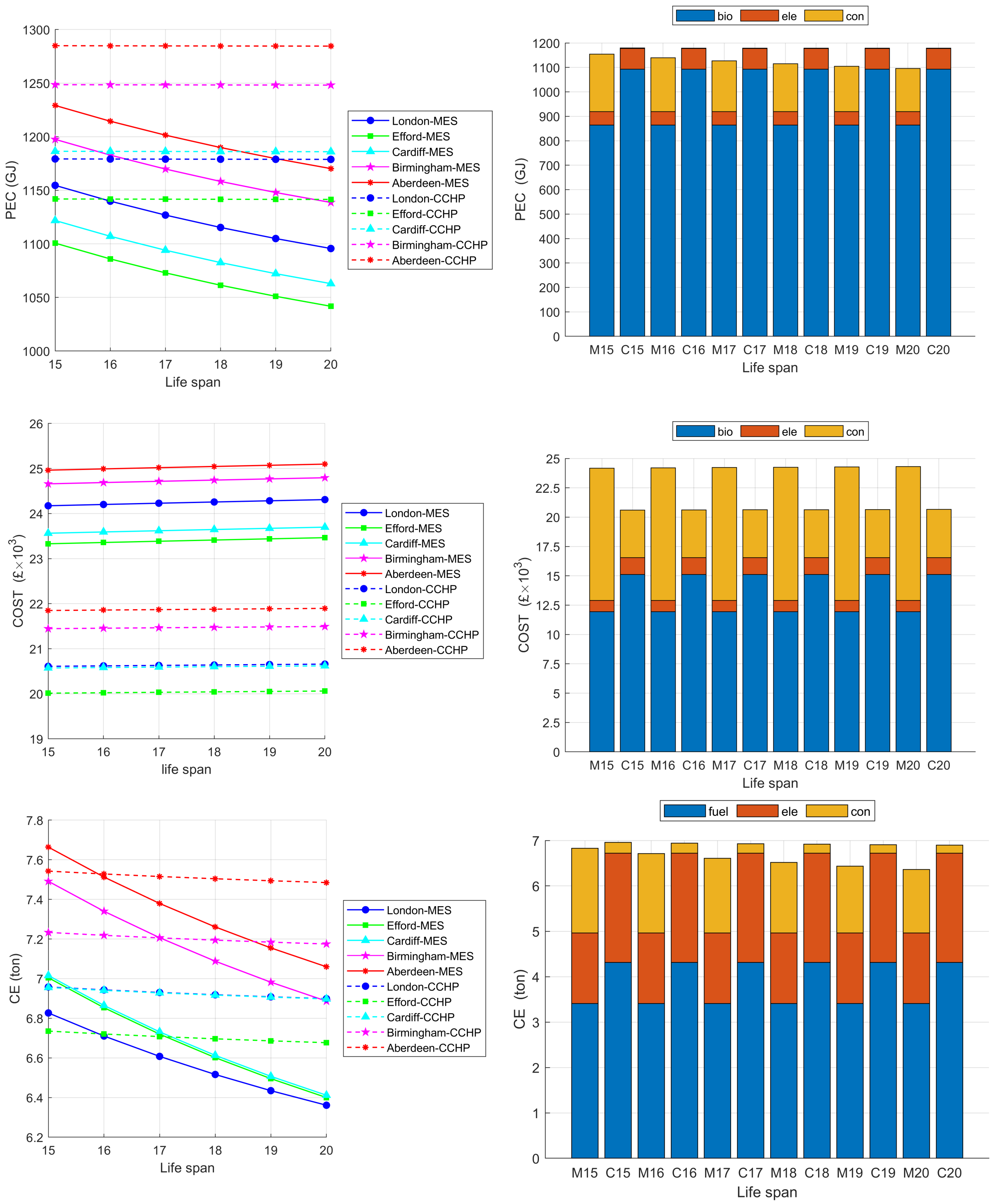


Fig. 13. Life cycle PEC, COST and CE at different life span.

The life span of energy devices has a significant effect on PEC, COST and CE on construction stage, while little effect on biomass and electricity consumption. When life span is decreased from 20 to 15, there is 33.33% increase of PEC and CE for constructing the MES and the reference CCHP system, while 1.20% decrease of COST for constructing the MES and the reference CCHP system. Due to the fact that PEC, COST and CE of the MES occupies a larger portion than those of the reference CCHP system, the increasing rate of PEC and CE of MES is much larger than that of the CCHP system with the decrease of life span. With shorter life span, the equivalent annual PEC and CE from construction stage becomes smaller, while the equivalent annual cost becomes relatively higher.

Table 16. Summary of sensitivity analysis regarding life span.

PEC	When ls decreased from 20 to 15	Construction	MES	↑33.33% (according to Eq. 6)
			CCHP	↑33.33% (according to Eq. 6)
		Life cycle	MES	↑0.03-0.04%
			CCHP	↑5.04-5.66%
	MES	Aberdeen > Birmingham > London > Cardiff > Efford		
	CCHP	Aberdeen > Birmingham > Cardiff > London > Efford		
	MES	Biomass > Construction > Electricity		
	CCHP	Biomass > Electricity > Construction		
	PEC of CCHP constantly higher than that of MES			
COST	When ls decreased from 20 to 15	Construction	MES	↓1.20% (according to Eq. 7)
			CCHP	↓1.20% (according to Eq. 7)
		Life cycle	MES	↓0.21-0.24%
			CCHP	↓0.53-0.58%
	MES	Aberdeen > Birmingham > London > Cardiff > Efford		
	CCHP	Aberdeen > Birmingham > London = Cardiff > Efford		
	MES	Biomass > Construction > Electricity		
	CCHP	Biomass > Construction > Electricity		
	COST of CCHP constantly higher than that of MES			
CE	When ls decreased from 20 to 15	Construction	MES	↑33.33% (according to Eq. 8)
			CCHP	↑33.33% (according to Eq. 8)
		Life cycle	MES	↑7.32-9.45%
			CCHP	↑0.77%-0.87%
	MES	Aberdeen > Birmingham > Cardiff > Efford > London		
	CCHP	Aberdeen > Birmingham > London = Cardiff > Efford		
	MES	Biomass > Construction > Electricity when ls = 20 Biomass > Electricity > Construction when ls < 20		
	CCHP	Biomass > Electricity > Construction when R_{rec} = 90%		
	CE of CCHP higher than that of MES only when R_{rec} > 80%			

4.3.4 Sensitivity analysis of interest rate

The composition of life cycle COST of the MES in London at different interest rate are summarized in Fig. 14. The rated capacity of PGU, recycle ratio and life span are kept constant at 50MJ/h, 90% and 20 years, respectively. The life cycle performance of economic cost of both MES and the reference CCHP system is summarized in Table 17.

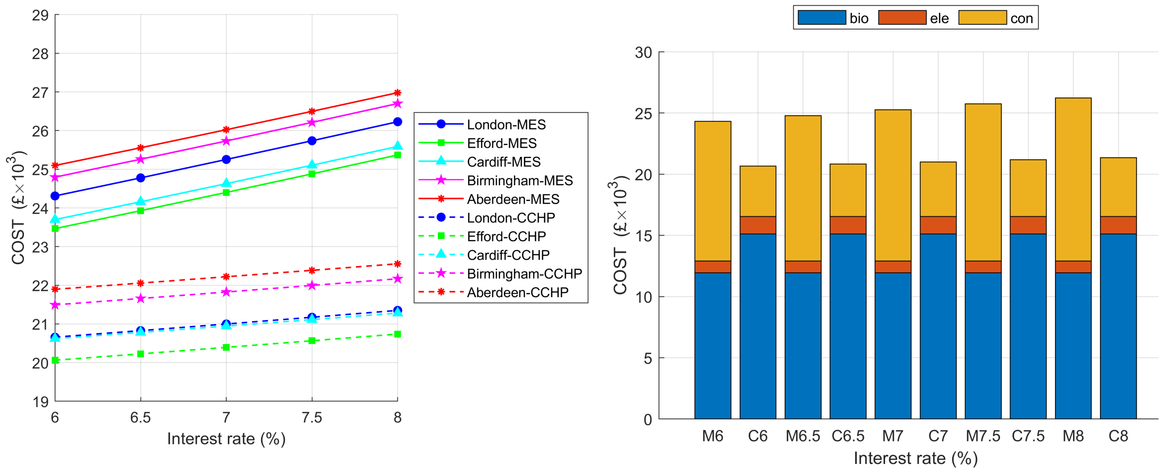


Fig. 14. Life cycle COST at different interest rate.

Table 17. Summary of sensitivity analysis regarding interest rate.

COST	When I decreased from 8% to 6%	Construction	MES	↓16.82 (according to Eq. 7)
			CCHP	↓16.82 (according to Eq. 7)
		Life cycle	MES	↓7.50%-7.98%
			CCHP	↓3.01% -3.38%
	MES	Aberdeen > Birmingham > London > Cardiff > Efford		
	CCHP	Aberdeen > Birmingham > London = Cardiff > Efford		
	MES	Biomass > Construction > Electricity		
	CCHP	Biomass > Construction > Electricity		
	COST of CCHP constantly higher than that of MES			

According to Eq. (7), the interest rate has a significant effect on cost during the construction stage, while little effect on the operating stage (i.e. cost of biomass and electricity). The interest does not have effect on PEC or CE, either. When interest rate decreased from 8% to 6%, there is 16.82% decrease of the construction cost for both MES and the reference CCHP system. Therefore, there is 7.50%-7.98% and 3.01%-3.38% decrease of life cycle cost for MES and the reference CCHP system, respectively.

5. Implication for practice and future direction

In this study, a comprehensive life cycle assessment approach is proposed for the renewable MES. There exists passive and active side of the MES, thus results in interrelated and complicated interactions in simultaneously satisfying heating, cooling and electrical energy demands in buildings. Being able to evaluate its life-long primary energy consumption, economic cost and carbon emission, the proposed life cycle assessment approach is quite helpful in retrofitting works of building energy systems.

The detailed process of life cycle assessment approach is summarized in Fig. 15. In practical application, the weather data and building information should be collected to estimate the year-round building energy demands and renewable energy productions. Thus, the appropriate multi-energy system can be designed while the operating schedule of each energy device can be determined. The proposed life cycle assessment approach can thus be applied to investigate the life cycle performance of primary energy consumption, economic cost and carbon emission during both the construction and operating stages. The recycle ratio of materials, life span of energy devices, and local interest rate have various impacts on the life cycle primary energy consumption, economic cost and carbon emission of MES. Through adopting the proposed life cycle assessment approach, the design capacity of energy devices could be determined according to their recycle ratio and life span, as well as local interest rate.

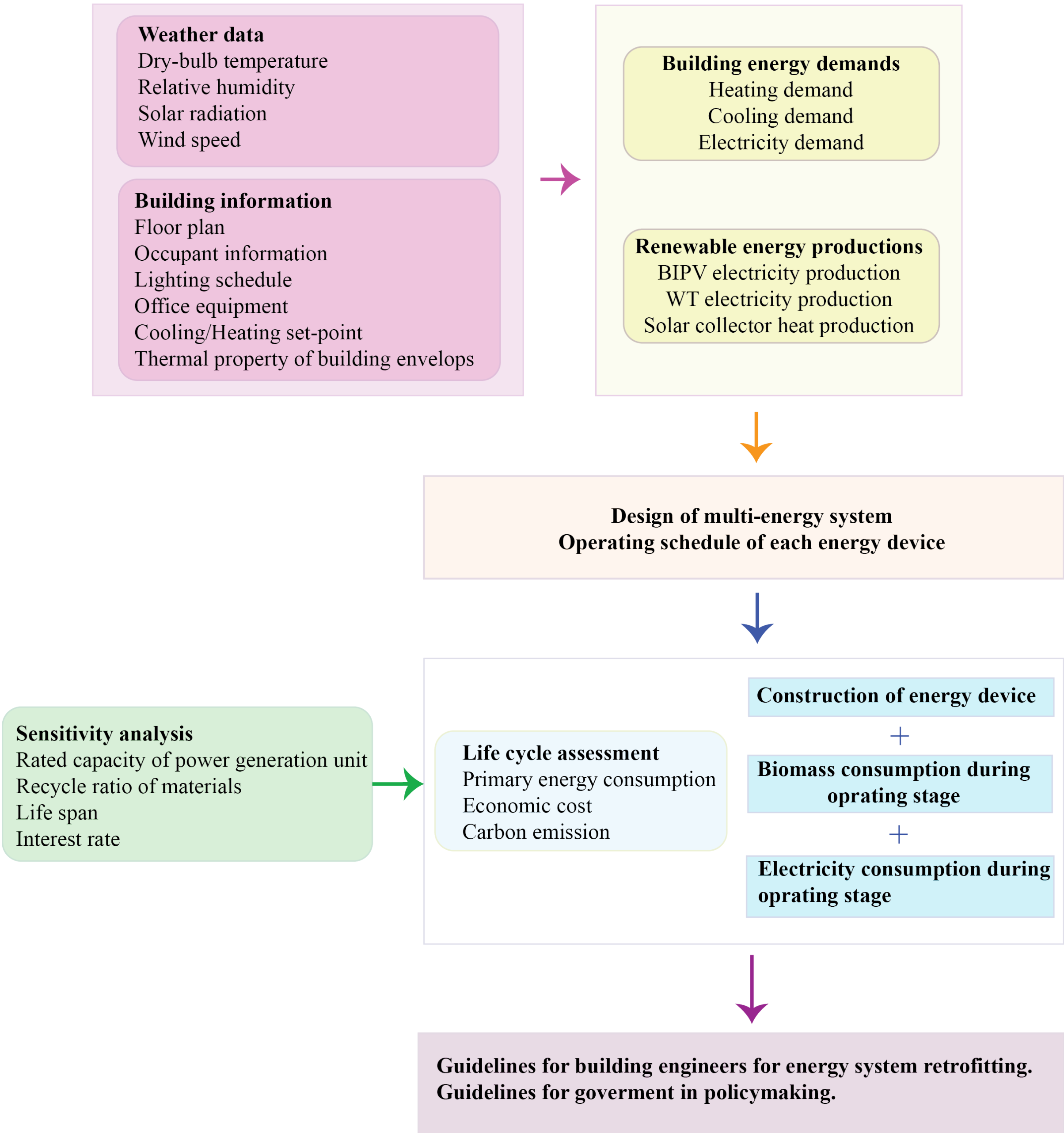


Fig. 15. Flowchart of proposed life-cycle assessment approach.

In this study, the modified following electricity load operating strategy is adopted to determine the operating capacity of energy devices, including biomass gasifier, power generation unit, absorption chiller, electric compression chiller and biomass boiler. To further improve the effectiveness of the renewable MES, the two-stage capacity optimization approach [1], multi-supply-multi-demand operating stage [2] as well as the integrated demand and supply side management strategy [3] can be coupled with the proposed life cycle assessment approach.

During the off-peak hours, the electricity produced by BIPV and wind turbine, as well as the heating energy produced by solar collector, are much higher than the corresponding electrical and heating energy demands. The energy storages can be installed to shift the off-peak energy production into peak periods. Therefore, the effects of energy storage on the life cycle performance of the MES can also be investigated.

6. Conclusion

In this study, a renewable MES is designed, which consists of both the passive and active sides. On the passive side, BIPV, wind turbine and solar collector are adopted to generate electrical and thermal energy, respectively. On the active side, the biomass PGU serves as the primary electricity supplier, while the thermal energy from exhaust gas and jacket water of the PGU is recovered to provide heat for both the absorption chiller and building application. The electric compression chiller and biomass boiler are adopted when the thermal energy from the CCHP system is not sufficient. The electricity is imported from the city power grid when the electrical energy provided by the MES itself is not sufficient.

A representative office building in the United Kingdom is chosen as the use case to evaluate the proposed life cycle assessment approach. Conventional life cycle assessment approach was mainly conducted at fixed condition and was focused on economy cost only. The novelty of the proposed life cycle assessment approach is that it can be adopted to conduct comprehensive analysis of life cycle primary energy consumption, economic cost and carbon emission for the renewable MES and any building energy system. To provide retrofitting suggestions for building energy system, this proposed approach is applied on five different cities in the UK. The sensitivity analysis regarding rated capacity of prime mover, life span, recycle ratio and interest rate is conducted based on local practical data. Key findings and practical suggestions are summarized as below:

- The life cycle PEC of MES has the 8%-11% and 13%-18% reduction compared to conventional separate system and CCHP system, respectively. The life cycle CE of MES has the 79%-81% and 21%-25% reduction compared to conventional separate system and CCHP system, respectively. However, the life cycle economy cost of MES has the 49%-61% and 12%-16% increase compared to conventional separate system and CCHP system, respectively.

- The PEC, COST and CE by consuming 1 kg biomass is 1.593 MJ, £ 0.26 and 0.056 kg, respectively. If the biomass PGU is operated at its maximum efficiency, the produced electrical and thermal energy from 1 kg biomass is 4.49 MJ and 6.12 MJ, respectively. It equals to 11.24 MJ, £ 0.156 and 0.737 kg PEC, COST and CE from city power grid plus 7.035 MJ, £ 0.048 and 0.355 kg PEC, COST and CE from natural gas boiler. Reducing the manufacturing cost of biomass or proving subsidy for biomass usage would encourage the wide adoption of biomass in building energy system thus to reduce overall primary energy consumption and carbon emission.
- The annual equivalent PEC and CE saving from BIPV, wind turbine and solar collector is higher than the corresponding PEC and CE during construction stage. However, the COST saving from these renewable energy devices is lower the COST during construction stage. Hence, the PEC and CE of MES is lower than the conventional separate system, while the COST of MES is higher. It is important in reducing the manufacturing cost of BIPV, wind turbine and solar collector. Moreover, subsidy should be provided by the government to encourage the utilization of BIPV, wind turbine and solar collector so as to help reduce primary energy consumption and carbon emission.
- Wind energy can be effectively utilized through the wind turbine for providing electrical energy, especially during the non-office hours when electricity demand is relatively low, and the biomass gasification based CCHP system is not operated;
- Owing to the lowest heating and electricity demand as well as the highest total solar radiation, Efford has the lowest PEC, COST and CE. On the contrary, Aberdeen results in the largest PEC, COST and CE.
- The PEC and CE of MES decreases with increase of recycle ratio and life span. Meanwhile, the COST decreases with the increase of life span while increases with the increase of interest rate.

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Nomenclature

C	capacity
CE	Carbon emission
C_p	specific heat of each molecule
COP	Coefficient of Performance
$COST$	Economic cost
LHV	Lower heating value
PEC	Primary energy consumption
PLR	part load ratio
q	heat

Q	energy rate
T	Temperature
α	heat loss coefficient of solar collector
φ	solar radiation
η	efficiency
ε	correction coefficient

Subscripts

amb	ambient
bg	biomass gasifier
BIPV	building integrated photovaltic
c	cooling
e	electricity
exh	exhaust gas
h	heating
in	input
jw	jacket water
n	rated
out	output
rec	heat recovery system
s	syngas
SC	solar collector

Abbreviations

AbC	absorption chiller
BIPV	building integrated photovoltaic
CCHP	combined cooling heating and power system
CE	carbon emission
CoC	electric compression chiller
ICE	internal combustion engine
MES	multi-energy system
PEC	primary energy consumption
PGU	power generation unit

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