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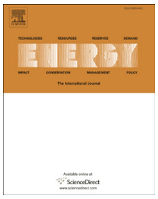

Optimal design of CHP-based microgrids: Multiobjective optimisation and life cycle assessment

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ABSTRACT

As an alternative to current centralised energy generation systems, microgrids are adopted to provide local energy with lower energy expenses and gas emissions by utilising distributed energy resources (DER). Several micro combined heat and power technologies have been developed recently for applications at domestic scale. The optimal design of DERs within CHP-based microgrids plays an important role in promoting the penetration of microgrid systems. In this work, the optimal design of microgrids with CHP units is addressed by coupling environmental and economic sustainability in a multi-objective optimisation model which integrates the results of a life cycle assessment of the microgrids investigated. The results show that the installation of multiple CHP technologies has a lower cost with higher environmental saving compared with the case when only a single technology is installed in each site, meaning that the microgrid works in a more efficient way when multiple technologies are selected. In general, proton exchange membrane (PEM) fuel cells are chosen as the basic CHP technology for most solutions, which offers lower environmental impacts at low cost. However, internal combustions engines (ICE) and Stirling engines (SE) are preferred if the heat demand is high.

1. Introduction

As an alternative to current centralised energy generation, microgrids can be adopted to provide energy locally by utilising distributed energy resources (DER). The DERs comprise several systems, such as energy generation, energy storage and load management options. The involved energy generation units are located near the end user [1]. They can be parallel to the standard electric grid or stand-alone units. Single units can be connected together in a microgrid system to serve small districts which can be powered independently from the standard electric grid. Natural gas is at present the primary fuel for DER, but renewable energy resources can be easily integrated allowing important environmental benefits in the power generation industry. One of the main applications of DER is the combined heat and power (CHP) generation, which increases the efficiency of the on-site power generation system using the waste heat for thermal energy production. A microgrid example is presented in Fig. 1. DER systems are growing fast in the UK. Distributed energy took about 9% of the total generation capacity in 2011; Verdantix, an independent energy analyst company, has forecasted that the total installed capacity of distributed energy technologies will increase to 17 GW by 2030, representing 14% of the expected UK generation capacity in 2030 [2]. However, DER systems face problems such as: large up-front capital cost, community acceptance and new technologies from pre-commercial stage [3]. The integration of different DER systems has led to the concept of microgrids which can minimise the negative impacts of single use DERs [4]. Hence, the optimal design of energy generation within microgrids plays an important role in promoting the penetration of microgrids. In particular, in order to meet renewable energy targets in the UK, the Government is considering the installation of CHP units because of their flexibility, reliability and safer operating conditions with high overall efficiencies [5]. Main CHP systems include traditional heat and power generators such as steam turbines, gas turbines, internal combustion engines and combined cycle system, as well as emerging technologies such as microturbines, Stirling engines and fuel cells [6]. Unlike engine CHP plants, fuel cells couple the advantages of reduced energy consumption with low direct emissions. Several

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Nomenclature

Indices

d	sample day
t	time interval
i	candidate CHP generator technology
k	CHP capacity level
s	site

Parameters

a^B	lifetime of boiler (year)
a_i^C	lifetime of CHP technology i (year)
a^T	lifetime of thermal storage (year)
c^I	price of electricity imported from the grid (£/kWh)
c^N	price of natural gas (£/kWh)
c^T	cost per unit output for thermal storage unit (£/kWh)
D^T	maximum discharge rate for thermal storage (kW)
F^B	capital recovery factor of the boiler
F_i^C	capital recovery factor of CHP technology i
F^T	capital recovery factor of the thermal storage
G^T	maximum charge rate for thermal storage (kW)
H_{dts}	heat demand of day d during time interval t at site s (kW)
L_{dts}	electrical demand of day d during time interval t at site s (kW)
M	big number
P	fixed cost for microgrid components (£)
Q_{ik}	heat to power ratio for CHP generator technology i of level k
r	interest rate
R_{ik}	ramp limit for CHP generator technology i from capacity level k (kW)
T_t	time duration of each time period t (h)
T_{ik}^{CHP}	maximum annual operation hours of CHP technology i at level k (h)
W_d	weight for day d (reflection of number of days of this type per year)
α_{ik}	cost of CHP generator technology i of level k (£/kW_e)
β	cost per kW_{th} installed for boiler (£/kW_{th})
γ	cost per $kW_{th}h$ installed for thermal energy storage (£/$kW_{th}h$)
η_{ik}^C	electrical efficiency of the CHP generator i of level k
η^B	efficiency of boiler
η^T	turn around efficiency of thermal energy storage
AP_i^{CHP}	use phase AP value of CHP technology i (*kg* SO_2 *equivalent/kWh fuel in*)
AP^B	use phase AP value of boiler (*kg* SO_2 *equivalent/kWh fuel in*)
AP^E	use phase AP value of electricity bought from grid (*kg* SO_2 *equivalent/kWh fuel input*)
AP^{BM}	manufacture phase AP value of boiler (*kg* SO_2 *equivalent/kW capacity*)
AP_i^{CHPM}	manufacture phase AP value of CHP technology i (*kg* SO_2 *equivalent/kW electricity capacity*)
AP^{TM}	manufacture phase AP value of thermal storage (*kg* SO_2 *equivalent/kWh capacity*)
GWP_i^{CHP}	use phase GWP value of CHP technology i (*kg* CO_2 *equivalent/kWh energy input*)
GWP^B	use phase GWP value of boiler (*kg* CO_2 *equivalent/kW fuel in*)
GWP^E	use phase GWP value of electricity bought from grid (*kg* CO_2 *equivalent/kWh electricity*)
GWP^{BM}	manufacture phase GWP value of boiler (*kg* CO_2 *equivalent/kW capacity*)
GWP_i^{CHPM}	manufacture phase GWP value of CHP technology i (*kg* CO_2 *equivalent/kW capacity*)
GWP^{TM}	manufacture phase GWP value of thermal storage (*kg* CO_2 *equivalent/kW capacity*)

Positive Variables

C_s^B	installed thermal capacity of boiler at site s (kW_{th})
C_{sik}^C	total installed electrical capacity of CHP i from level k at site s (kW_e)
C_s^T	installed capacity of thermal energy storage unit at site s ($kW_{th}h$)
f_{dts}	heat received from the thermal storage on day d at time t at site s (kW_{th})
g_{dts}	heat sent to the thermal storage on day d at time t at site s (kW_{th})
h_{dts}	heat dumped on day d at time t at site s (kW_{th})
I_{dt}	electricity imported from the grid on day d at time t for site s (kW_e)
S_{dts}^T	heat stored in the thermal storage on day d at time t at site s ($kW_{th}h$)
u_{dtsik}	output of CHP i on day d at time t at site s from CHP technology k (kW_e)
x_{dts}	output of boiler on day d at time t at site s (kW_{th})
ϕ_1	objective 1, total equivalent annual cost (£)
ϕ_2	objective 2, total GWP (kg CO_2 equivalent)
ϕ_3	objective 3, total AP (kg SO_2 equivalent)
ACC	annual capital cost (£)
EAC	equivalent annual cost (£)
EC	electricity cost of site s(£)
OPC	operation cost of site s(£)

Binary variables

X_{dtsik}	1 if for site s CHP technology i level k is operating on day d time t; 0 otherwise
Y_{dt}^I	1 if electricity is imported from the grid on day d time t; 0 otherwise
Z_{si}	1 if site s CHP technology i is selected; 0 otherwise

Integer variable

N_{sik}	number of CHP generators at site s of CHP technology i from level k

CHP technologies have been developed recently for applications at domestic scale, including fuel cells, micro turbines, internal combustion engines and Stirling engines. As a result, micro CHP generation can lead to significant reduction in CO2 emissions: field trials in Japan have demonstrated annual reductions of 750–1250 kg CO2 per household as a consequence of using 1 kWe fuel cells [7]. Compared with large power plants, micro-CHPs are more efficient in using thermal energy at domestic scale without being transported [8]. It has been specifically suggested that the replacement of gas heating boilers may open up a new mass market for micro-CHPs [9]. At present, the UK is the largest European boiler market, with 17 million systems currently installed and 1.6 million boilers sold annually, primarily due to the UK's aversion to heat distribution systems. In the Carbon Trust's Micro-CHP Accelerator project, 87 micro-CHP systems have been installed and monitored in households and small commercial applications in the UK [10].

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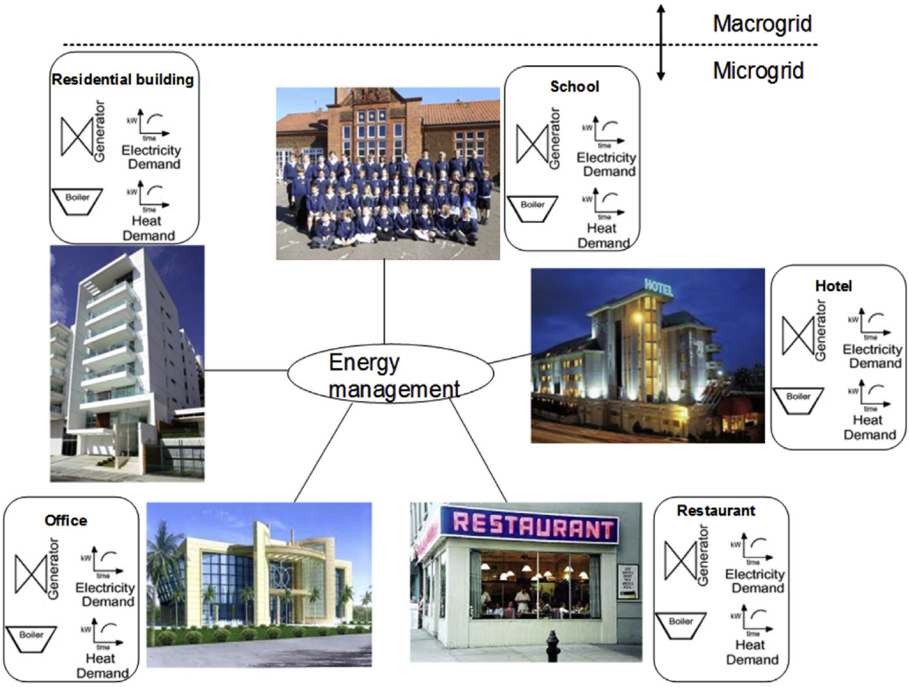

Fig. 1. Example of a microgrid.

The Department of energy and climate change (DECC) has estimated that the implementation of micro CHP systems in the UK might reduce emissions of CO_2 by up to 2.1 tons per year per household compared to condensing boilers and electricity drawn from the grid [5]. However, CHP technologies are still at an early stage of market development and currently face adverse market conditions, having to compete with already available energy systems, although being more cost effective. A further challenge is decreasing the installation costs through either the economies of scale or optimised designs and manufacture in order to attract a large number of investors. Robust support is necessary for the penetration of CHP systems, such as CHP initial boost, benefits reflection and consumer incentive enhancement [11]. In order to gain the optimum benefit from CHP applications in residential and small buildings, the selection of the most suitable CHP technologies in the microgrid is therefore key. Moreover, the optimal design of the microgrids becomes a multi-objective problem when conflicting objectives need to be optimised simultaneously. This paper tackles the design of a CHP-based microgrid system addressing both economic and environmental concerns through the entire life time of the microgrid.

1.1. Optimal design and planning of microgrids

The capacity design of a microgrid system has been studied recently where only annual cost is minimised [12–14]. Under the cost minimisation objective, the equipment arrangement of each building within a fuel cell network is optimised along with a hot-water piping network using genetic algorithm (GA) [15]. An MILP (multi-objective mixed-integer linear programming) model for optimal DER design is presented in Ref. [16] for a small neighbourhood, which include micro CHP units, back-up boilers and PV units. It also provides the design of the heating pipeline network for transporting heat between different nodes. Proper CHP-based DERs are deployed in Ref. [17] through optimisation with particle swarm optimisation (PSO) technique on the basis of maximisation of benefit to cost ratio, where benefit and cost are related to optimal CHP-based DERs deployment. Methodology for optimal DER selection and capacity sizing is proposed in Ref. [18] for integrated microgrids using evolutionary strategy (ES), where several microgrids are interconnected with each other for superior control and management. Energy limits and emission limits are treated as hard constraints there. A mathematical model is formulated in Ref. [19] for fair, optimised cost distribution among participants in a general microgrid based on the Game-theory Nash bargaining solution approach. The participants within the microgrid are considered as collaborators among themselves.

Besides the optimal design of microgrids, operation planning and power quality evaluations are addressed in several studies based on various methods. Hawkes and Leach [20] presented a linear programming cost minimisation model, which also provides the optimised operating schedule. A Monte Carlo analysis is applied to consider the impact of inclusion of intermittent sources along with the sensitivity analysis of energy price variation. An Orthogonal array-GA hybrid method is applied to optimise equipment capacity selection and operational methods in Refs. [21], and it indicates that the hybrid method has good convergence characteristics than simple GA based on the comparison. Sheikhi et al. [22] proposed a model to find the optimal size and operation of DERs with the consideration of electricity and gas network based on the energy hub concepts. Service reliability can be improved while the power cost can be reduced. By applying differential evolutionary algorithms, Basu [23] presented a strategic deployment of DERs in a microgrid where the owner of the microgrid could make a schedule of DERs at different optimal fuel costs for either Mix-DER group or all-diesel generator. Authors of [24] presented a strategy to obtain the optimal DER and reactive power injection locations based on evolutionary optimisation methods, which improves both voltage stability of the system and the DER penetration level. Loss reduction was maximised in Ref. [25] using PSO for the DERs location and size selection while the voltage profile of the system is improved. Finally, in Ref. [26] generation design within microgrids was addressed with the power reliability and voltage quality analyses and the model has been implemented using PSCAD software.

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However, the limitation of these studies is again that only cost minimisation is considered while an environmental evaluation is entirely missing.

Amongst the studies that encompassed environmental aspects, Bando et al. [27] developed a methodology for the designing of DER in microgrid with steam supply from a municipal waste incinerator, and both primary energy consumption and CO_2 emissions have been reduced. Sizing and scheduling of DER within microgrid was obtained in Refs. [28], where electricity vehicles are integrated. However in both works, only single objective model which minimise cost was considered, while CO_2 emissions reduction was analysed from the post-optimisation calculation. Mizani and Yazdani [29] demonstrated the optimal selection of DER in a grid connected microgrid together with optimal dispatch strategies and they could reduce microgrid lifetime cost and emission on a campus with weighting factor method. Guo et al. [30] presented a planning and design method based on non-dominated sorting genetic algorithm-II to minimise the total net present cost and carbon dioxide emissions of a microgrid with a single customer. However, their models did not consider the possibility to select the CHPs in the microgrid based on their own characteristics and in conjunction with their life cycle assessment.

1.2. *Environmental impact assessment*

Different tools exist to evaluate the environmental impacts of a process or a service. Life Cycle Assessment (LCA) is recognised as one of the best tools available for comparing the impact of alternative technologies [31,32], it helps avoiding burdens shifting, i.e. ‘minimizing impacts at one stage of the life cycle, or in a geographic region, or in a particular impact category, while helping to avoid increases elsewhere [33]. LCA quantifies the amount of materials and energy used over the complete supply chains (i.e. life cycles) of goods and services and identifies emissions and wastes associated with the life cycles. The International Standards ISO 14040 and 14044 [34] provide the methodological framework for LCA applications and define its main phases: goal and scope definition; life cycle inventory; life cycle impact assessment; and Interpretation and Improvement.

Studies have been published on carbon footprint of micro – CHP units rather than a holistic environmental appraisal [35–37]. A few studies focused on the environmental impacts of different micro-CHP technologies analysing the functioning of single units rather than microgrids [9,38]. Moreover, limited studies in the literature have been focused on coupling environmental and economic sustainability in a multi-objective optimisation model: the majority of them focussing on the operation of a single unit. Jing et al. [39] analysed a building cooling heating and power system. Bernier et al. [40] applied the full LCA perspective to study the integration of a CO2-capture process using monoethanolamine in a natural gas-combined cycle power plant. Some authors approached the problem of microgrids from a wider perspective, applying more a sustainability assessment methodology rather than a multi-objectives optimisation. Lo Prete et al. [41] developed a framework to assess and quantify the sustainability and reliability of different power production scenarios in a regional system, focussing on the interaction of microgrids with the existing transmission/distribution grid rather than different specific technologies. Ristimaki et al. [42] approached the problem from a life cycle perspective only, integrating life cycle costing with life cycle analysis but with no optimisation methodology. To our knowledge, no studies have been published on the optimal design of CHP-based microgrids which integrates environmental (i.e. life cycle assessment) and economic metrics through optimisation methodology.

1.3. *Objective of this study*

Optimal design of energy systems with environmental concern for the entire life cycle is becoming more and more important. LCA is used to quantify and evaluate the environmental performance of a product or a process for its entire life cycle and it provides the basis for assessing potential improvements. On the other hand, system optimisation focuses on economic objectives [43,44]. The integration of LCA into optimisation framework provides a powerful decision-making tool to identify an optimal process configuration conceiving both environmental and economic aspects ‘from cradle to grave’ [45]. In this work, we address the optimal design of microgrids with CHP generators considering both environmental and economic concerns. Life cycle assessment methodology is used to evaluate the environmental impacts of different microgrid designs which are then optimised based on economic metrics through a multi-objective modelling framework. Different methodologies can be applied to solve the multi-objective optimisation problem, including the ε-constraint method [29,46] and weighted sum method [47]. Here, the trade-off between two conflicting objectives, minimising the cost and minimising the environmental impact of the microgrid, is obtained by solving the proposed model with both methods.

The remainder of this paper is organised as follows: In Section 2, life cycle assessment of microgrids is described. In Section 3, the problem description is presented with relevant assumptions, constraints and the objective function. In Section 4, the mathematical model is provided. Then in Section 5, the proposed model is applied to a microgrid case with five sites and the computational results are shown in Section 6. Finally, concluding remarks are given in Section 7.

2. Life cycle assessment of microgrids

In LCA, a multifunctional process is defined as an activity that fulfils more than one function, such as micro CHP technologies which can produce electricity and heat at the same time. It is then necessary to find a rational basis for allocating the environmental burdens between the functions or products. The ISO standards recommend that the environmental benefits of recovered resources should be accounted for by broadening the system boundaries to include and compare the burdens of conventional production, an approach referred as system expansion [48]. The same approach is recommended for product labelling provided that it can be proved that the recovered material or energy is actually used [49]. This approach is applied here. Following the methodological approach of Clift et al. [33], a pragmatic distinction between Foreground and Background is made in this study, considering the first as ‘the set of processes whose selection or mode of operation is affected directly by decisions based on the study’ and the second as ‘all other processes which interact with the Foreground, usually by supplying or receiving material or energy.

The goal of this LCA is to estimate the environmental impacts of four different CHP systems with an additional boiler and a thermal energy storage working in a distributed generation network. The technologies investigated are: a proton exchange membrane (PEM) fuel cell; a solid oxide fuel cell (SOFC); Stirling engine (SE); and internal combustion engine (ICE). The impact categories analysed in this study are the global warming potential (GWP), which is an indicator of the greenhouse effect, and the acidification potential (AP) as an indicator of acid rain and deposition [50].

The system boundary is shown in Fig. 2. Both the manufacturing and the use phase are considered in this study. A reference scenario for the supply of electricity from the grid and heat from a condensing boiler with natural gas is included in the background for comparison with the microgrid. Following the methodological approach of Clift et al. [33] for Integrated Waste Management, a pragmatic distinction between Foreground and Background is made in this study, considering the first as 'the set of processes whose selection or mode of operation is affected directly by decisions based on the study' and the second as 'all other processes which interact with the Foreground, usually by supplying or receiving material or energy'. Defining the functional unit is a key step in every LCA study. Input or output flows can be selected as functional unit, based on the purpose of the study and the system boundary [50]. The functional unit used in this study is one MJ of natural gas as input to the micro CHP system. Choosing this functional unit avoids to introduce allocation on the two by products, i.e. electricity and heat. Moreover, system expansion is applied in this study as recommended by ISO 14040 [34].

2.1. *Life cycle inventory*

The data for the life cycle inventory are based on the Ecoinvent dataset [51]. The manufacturing phase includes the production of the energy system (boiler, CHP and thermal energy storage), the transport of the materials and the energy needed for its production and engineering. The production process involves raw material cutting, casting, machining and welding. The use phase includes the supply of natural gas to the micro CHP system and to the additional condensing boiler, then the direct use of the CHP generator.

For the reference scenario, the average mix of technologies used to produce 1 kWh of electricity from the grid is assumed. In the UK, at the present the electricity is mainly produced from natural gas (44%), hard coal (28%) and nuclear energy (18%) [52]. The production of heat is evaluated considering a natural gas-fired condensing boiler with an efficiency of 85% [37]. In the UK more than half of the natural gas comes from national resources, giving a lower carbon footprint for the production of 1 kg of natural gas compared with other European countries [7].

2.2. *Life cycle impact assessment*

The environmental impacts shown in Tables 1 and 2 are the results of the LCA, which has been performed using GaBi 6.0 sustainability software [52]. The environmental impacts shown in Tables 1 and 2 are valid for the system boundary shown in Fig. 2 and they are used as an input for the optimisation model. GWP and AP impacts for the manufacturing and use phase of the different micro CHP technologies investigated are given, as well as for the reference scenario.

From the environmental view point, initially only the global warming potential is considered in the optimisation model. Then the two LCA impact factors, GWP and AP, are aggregated into a single index through the weighted sum method while taking into account that the two impact factors have different importance. This method scalarises the two objectives into a single objective by multiplying each objective with a user supplied weight. Different methodologies exist to determine the weighting factor, the one applied in this study is based on CML – PE survey 2012 [52], as shown in Table 3.

3. Problem description

In this study, we consider the optimal design of microgrids with CHP units coupling environmental and economic sustainability in a multi-objective optimisation model which applies the LCA results of the microgrids as input. A general microgrid is addressed, which involves several participant sites as shown in Fig. 1. They are different types of buildings, which can be dwellings, schools and shops. The microgrid considered in this work is assumed to include an energy management system, local controllers for each energy source and communications system that can provide an optimal energy production schedule. The macrogrid is available to provide electricity to the participant in the microgrid. The candidate technologies include CHP generators (with different technical characteristics), boilers, thermal storage and a macrogrid power connection. The microgrid and the macrogrid are connected and constrained through importing electricity.

Energy production is modelled on specific sample days. The assumptions made for each participant are listed below:

- up to one boiler;
- up to one thermal storage;
- a grid connection (allowing electricity importation, but no exportation);
- no heat transfer between sites;

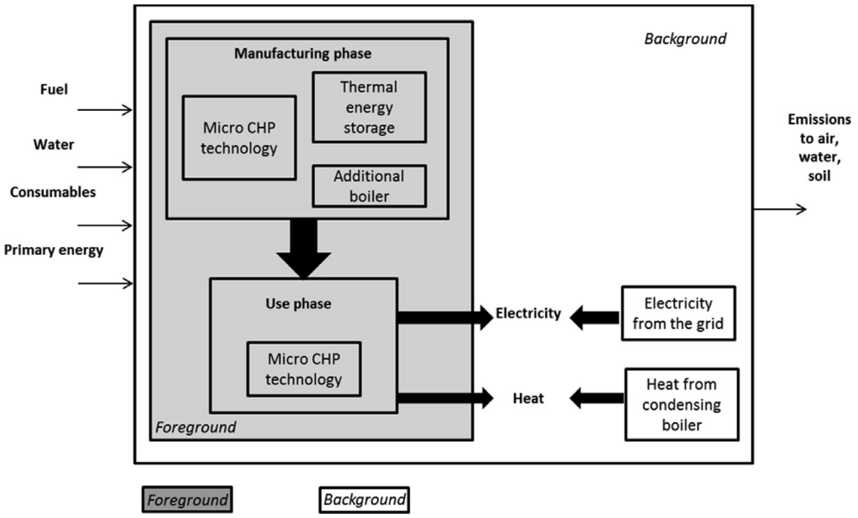

Fig. 2. System boundary considered for the LCA.

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Table 1
GWP impacts for the micro CHP technologies and the reference scenario.

	GWP manufacture phase (kg CO_2 eq/kW capacity)	GWP use phase
Electricity from the grid	–	0.565 kg of CO_2 eq per kWh of electricity
Natural gas from the grid	–	0.0158 kg of CO_2 eq per kWh of natural gas produced -
PEM	1160	0.218 kg CO_2 eq/kWh fuel in[a]
SOFC	665	0.218 kg CO_2 eq/kWh fuel in[a]
ICE	4290	0.225 kg CO_2 eq/kWh fuel in[a]
SE	910	0.202 kg CO_2 eq/kWh fuel in[a]
Condensing boiler	38	0.264 kg CO_2 eq/kWh fuel in[a]
Thermal energy storage	49.2	

[a] Note: Including the production of natural gas.

Table 2
AP impacts for the micro CHP technologies and the reference scenario.

	AP manufacture phase (kg SO_2 eq/kW capacity)	AP use phase
Electricity from the grid	–	0.00183 kg of SO_2 eq per kWh of electrical output
Natural gas from the grid	–	4.02E−05 kg of SO_2 eq per kWh of natural gas produced
PEM	8.77	5.40E−05 kg SO_2 eq/kWh fuel in[a]
SOFC	4.64	5.54E−05 kg SO_2 eq/kWh fuel in[a]
ICE	35.7	9.90E−05 kg SO_2 eq/kWh fuel in[a]
SE	3.32	2.00E−5 kg SO_2 eq/kWh fuel in[a]
Condensing boiler	0.221	0.000206 kg SO_2 eq/kWh fuel in[a]
Thermal energy storage	0.189	–

[a] Note: Including the production of natural gas.

Table 3
Weighting factors for GWP and AP applied in this study [52].

	Weighting factors
GWP	8.8
AP	5.7

A multi-objective mixed-integer linear programming (MILP) approach is developed for this study. The key decision variables include the selection of the technology and the capacity of the micro- CHP unit (see Table 5). They are determined by minimising the total equivalent annualised cost (EAC), GWP and AP impacts of all the participants in the microgrid. The trade-off between the economic and environmental objectives is then analysed with a set of Pareto-optimal solutions.

The overall optimisation problem can be stated as follows, which includes the 'known', 'to be determined', and objective functions:

Given (a) a time horizon split into a number of intervals (not necessary equal); (b) the energy demand of each participant for each time interval; (c) the natural gas and the electricity costs from the macrogrid; (d) the turn-key costs; (e) the energy efficiencies; (f) the heat-to-power ratio; (g) the ramp limits for each CHP generator considered in the study; (h) the charge and discharge rates for the thermal storage; (i) the fixed costs for the microgrid components; (j) the weighting factor for each day type and (k) the environmental impact, such as GWP and AP of the manufacturing and use phase of the CHP generators;

Table 4
Description of EAC_s components.

Respective term calculation	Description
$ACC^{CHP} = \sum_{sik}(\alpha_{ik}F^C C^C_{sik})$	Annual capital cost of CHP generator
$ACC^B = \sum_{s} \beta F^B C^B_s$	Annual capital cost of boiler
$ACC^{THS} = \sum_{s} \gamma F^T C^T_s$	Annual capital cost of thermal storage
$OPC^{CHP} = \sum_{dtsik} c^N W_d T_t u_{dtsik} / \eta^C_{ik}$	Operation cost of CHP generator
$OPC^B = \sum_{dts} c^N W_d T_t x_{dts} / \eta^B$	Operation cost of boiler
$OPC^{THS} = \sum_{dts} c^T W_d T_t g_{dts}$	Operation cost of thermal storage
$EC = \sum_{dt} c^I W_d T_t I_{dt}$	Electricity cost from macrogrid

Determine (a) the candidate technologies selected and their capacities; (b) the energy resources consumed (i.e. electricity imported from the grid); (c) the energy production plan (i.e. the utilisation factors of the CHP generators and the heat dumping[1]); and (d) the thermal energy storage plan.

In order to (a) find the optimum microgrid design with minimum environmental impact and total cost and to (b) fulfil the energy demand (both heat and electricity) of the participants in the microgrid.

4. Optimisation model

The mathematical formulation of the optimisation model is provided in this section, including the constraints and the objective functions.

4.1. Capacity constraint

The electricity and heat produced by the CHP generators and the additional boilers over any period on any day at each participant site cannot exceed their installed unit capacities (Eqs. (1) and (2)). For the CHP generators, the total capacity is the sum of all the CHP generator capacities within the same technology in the same capacity range.

$$u_{dtsik} - C^C_{sik} \leq 0 \quad \forall d, t, s, i, k \tag{1}$$

Heat produced from the boilers is limited by their designed capacities:

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[1] In this work "heat dumping" is referred to the surplus heat produced by the CHP generator which is not used to satisfy the heat demand of the microgrid sites.

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Table 5
Basic technical parameters and costs of microgrid candidate technologies [20,56].

Technology (kW)	Turn-key cost (£/kW)	Operating cost (£/kWh)	Electrical efficiency	Overall efficiency	Lifetime (year)	Reference
Boiler	40	0.027	–	0.80	15	
Thermal storage	20	0.001	0.98	–	25	
PEM (2–5)	2981	0.027	0.32	0.87	15	[57]
PEM (5–10)	994	0.027	0.4	0.87	15	[57]
SOFC (2–5)	5520	0.027	0.4	0.80	15	[58]
SOFC (5–10)	1840	0.027	0.47	0.80	15	[58]
ICE (2–5)	866	0.027	0.15	0.90	22	[59]
ICE (5–10)	700	0.027	0.2	0.90	22	[59]
ICE (10–15)	600	0.027	0.23	0.90	22	[59]
ICE (15–20)	534	0.027	0.25	0.90	22	[59]
SE (2–5)	1980	0.027	0.15	0.90	15	[60,61]
SE (5–10)	1300	0.027	0.2	0.90	15	[60,61]

$$x_{dts} - C_s^B \le 0 \quad \forall d,t,s \tag{2}$$

At any time on any day at each participant site, the heat stored cannot exceed the installed capacity of the thermal storage unit (as shown in Eq. (3)).

$$S_{dts}^T \le C_s^T \quad \forall d,t,s \tag{3}$$

4.2. Ramp limit constraint

The degradation of the CHP generator performances with time can affect significantly the economics of ownership [53,54]. In order to avoid the damage of the generator and the unit degradation, the CHP generator outputs between two adjacent time intervals are constraint to change within a range. The output difference between the two time intervals is limited by the given lower and upper limits. These ‘ramp limits’ for each CHP generator capacity range are given as:

$$-R_i \le u_{d,t+1,s,i,k} - u_{dtsik} \le R_i \quad \forall d,t,s,i,k \tag{4}$$

The thermal storage charge and discharge rates are the rates at which heat is added to or removed from the thermal storage. These charge and discharge rates depend on the characteristics of the specific thermal storage equipment; so the two rates are limited by constraints Eqs. (5) and (6):

$$f_{dts} \le D^T \quad \forall d,t,s \tag{5}$$

$$g_{dts} \le G^T \quad \forall d,t,s \tag{6}$$

4.3. Energy demand constraint

For each time interval, the electricity demand of the participant sites equals the sum of the electricity outputs of the CHP generators and the electricity imported from the macrogrid, as shown in Eq. (7).

$$\sum_{sik} u_{dtsik} + I_{dt} = \sum_{s} L_{dts} \quad \forall d,t \tag{7}$$

The heat demand of the participant sites and the dumped heat equal the sum of heat output of the CHP generators, the heat output of the additional boilers and the heat discharged from the thermal storage minus the heat sent to the thermal storage. The heat generated from CHP generators is calculated by multiplying the electricity output with the heat-to-power ratio Q_{ik} of each type of CHP generator, as shown in Eq. (8).

$$\sum_{ik} Q_{ik} u_{dtsik} + f_{dts} - g_{dts} + x_{dts} = H_{dts} + h_{dts} \quad \forall d,t,s \tag{8}$$

4.4. CHP constraints

For each type of CHP generator, the annual operation hours is limited based on their lifetime. So if the CHP generator of technology i from capacity level k is operated on day d time period t at site s, then the operation hours is counted once for that period. The total operation hours increase with the number of CHP generators, as shown in Eqs. (9) and (10). The weighting factor and time duration is multiplied in Eq. (10) to obtain the total operation hours.

$$u_{dtsik} - MX_{dtsik} \le 0 \quad \forall d,t,s,i,k \tag{9}$$

$$\sum_{dt} X_{dtsik} W_d T_t \le N_{sik} T_i^{CHP} \quad \forall s,i,k \tag{10}$$

The total capacity of CHP generators at the same capacity range should be within selected range multiplied with the number of unites within the same range (Eq. (11)).

$$C_{ik}^{C\min} N_{sik} \le C_{sik}^{C} \le C_{ik}^{C\max} N_{sik} \quad \forall s,i,k \tag{11}$$

The following two constraints are included, if at most one technology can be selected for each site Z_{si}, while the number of the CHP generators is not limited for that technology but if the technology is not selected, no CHP generator capacity can be selected (Eqs. (12) and (13)).

$$\sum_{i} Z_{si} \le 1 \quad \forall s \tag{12}$$

$$\sum_{k} C_{sik}^{C} \le MZ_{si} \quad \forall s,i \tag{13}$$

4.5. Thermal storage constraints

For each participant site at each time interval, the energy stored in the thermal storage is the sum of the energy stored from the previous time period and the energy charged into the storage minus the energy discharged from the storage. Heat losses are considered based on the efficiency during the charging and discharging processes. For example with the thermal storage turn-

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around efficiency η^T, during any period when the amount of heat $T_t g_{dts}$ is sent to the thermal storage, only $T_t \eta^T g_{dts}$ will be charged, and the rest being lost. On the other hand during the discharging process, in order to send $T_t f_{dts}$ of heat to the site, $T_t / \eta^T f_{dts}$ of heat is sent, as shown in Eq. (14).

$$S^T_{dts} = S^T_{d,t-1,s} + T_t \eta^T g_{dts} - T_t \Big/ \eta^T f_{dts} \quad \forall d,t,s \tag{14}$$

In order to guarantee that no heat is accumulated day to day, the thermal storage has an initial storage state at the beginning of each sample day; at the end of the day, the thermal storage must return to its initial value, as in Eq. (15).

$$S^T_{d,0,s} = S^T_{d-1,T,s} \quad \forall d,s \tag{15}$$

4.6. Objective functions

The ε-constraint method pre-defines a virtual grid in the objective space and solves different single-objective problems constrained to each grid cell. All Pareto-optimal solutions can be found only if this grid is fine enough such that at most one Pareto-optimal solution is constrained in each cell. The approach of optimising the design of a microgrid involves minimising the total cost of all participants as shown in Eq. (16).

$$\phi_1 = ACC^{CHP} + ACC^B + ACC^{THS} + OPC^{CHP} + OPC^B + OPC^{THS} + EC + P \tag{16}$$

where P is the fixed cost for the microgrid components. Details of each term are provided in Table 4.

The second objective function is to minimise the total GWP of the micrgrid components as Eq. (17) which include the GWP from use phase and manufacture phase of CHP generators, boilers and thermal storage along with GWP from imported electricity from grid:

$$\begin{aligned}\phi_2 = {} & \sum_{dtsik} W_d T_t GWP^{CHP}_i u_{dtsik} \Big/ \eta^C_{ik} + \sum_{dts} W_d T_t GWP^B x_{dts} \Big/ \eta^B \\ & + \sum_{dt} W_d T_t GWP^E I_{dt} + \sum_{sik} GWP^{CHPM}_i C^C_{sik} \Big/ a^C_i \\ & + \sum_s GWP^{BM} C^B_s \Big/ a^B + \sum_s GWP^{TM} C^T_s \Big/ a^T\end{aligned} \tag{17}$$

The third objective function is to minimise the total AP of the microgrid components as Eq. (18) which include the AP from the use phase and manufacture phase of CHP generators, boilers and thermal storage along with AP from imported electricity from grid:

$$\begin{aligned}\phi_3 = {} & \sum_{dtsik} W_d T_t AP^{CHP}_i u_{dtsik} \Big/ \eta^C_{il} + \sum_{dts} W_d T_t AP^B x_{dts} \Big/ \eta^B \\ & + \sum_{dt} W_d T_t AP^E I_{dt} + \sum_{sik} AP^{CHPM}_i C^C_{sik} \Big/ a^C_i + \sum_s AP^{BM} C^B_s \Big/ a^B \\ & + \sum_s AP^{TM} C^T_s \Big/ a^T\end{aligned} \tag{18}$$

The above three objective functions are considered in a multi-objective formulation as

$$\underset{x \in Q}{Min} \{\phi_1(x), \phi_2(x), \phi_3(x)\} \tag{19}$$

where x is the vector of decision variables and Q is the space of feasible solutions defined by the following constraints.

4.7. The ε-constraint method with two objectives

Applying the ε-constraint to the proposed multi-objective problem $\underset{x \in Q}{Min}\{\phi_1(x), \phi_2(x)\}$ it keeps ϕ_1 as the objective function, while ϕ_2 is considered as a constraint. A single-objective function is obtained as:

$$\begin{aligned} & \min_{x \in Q} \quad \phi_1(x) \\ & \text{s.t.} \ \ \phi_2(x) \le \varepsilon_2 \end{aligned} \tag{20}$$

By minimising ϕ_1 and ϕ_2 individually, the maximum and minimum values of ϕ_2 are obtained, which are used to define values of ε_2. For each point M+1: ε_2 is calculated from $\varepsilon_2 = \phi_2^{\max} - \frac{\phi_2^{\max} - \phi_2^{\min}}{M} \lambda$, where M is the number of self-defined intervals between the maximum and minimum values of ϕ_2 and $\lambda = 0,...,M$.

If ϕ_2 and ϕ_3 are considered in a comprehensive constraint representing environmental aspect, with weighting factors w_2 and w_3 respectively. A single-objective function is obtained as:

$$\begin{aligned} & \min_{x \in Q} \quad \phi_1(x) \\ & \text{s.t.} \ \ \phi_{23} = w_2 \phi'_2(x) + w_3 \phi'_3(x) \le \varepsilon_{23} \end{aligned} \tag{21}$$

where $\phi'_2 = \frac{\phi_2}{\phi_2^{\min}}$ and $\phi'_3 = \frac{\phi_3}{\phi_3^{\min}}$, $\phi_2^{\min}$ and $\phi_3^{\min}$ are obtained by minimising ϕ_2 and ϕ_3 from Eqs. (17) and (18) individually, w_2 and w_3 are weighting factors. Values of ϕ_{23} are defined similarly as those of ϕ_2 explained above for ε_2.

5. Case study

The proposed models have been implemented for a case study, including a school, a hotel, a restaurant, an office building and a residential building. All the buildings are built to Passivehaus standards according to information provided by the developers [55]. The energy demand profiles are the same as given in Refs. [19], which is provided by authors of [55] as shown in Appendix.

5.1. Technical characteristics and costs of the microgrid CHP generators

The parameters for the CHP, boiler and thermal energy storage are presented in Table 5. The life span considered is 15 years. Turnkey cost includes the costs of investment, installation, foundations and main connections. Operating costs for CHP generators and boilers are assumed to comprise only the fuel cost. For the fuel cost, the gas price assumed is 2.7 *p/kWh* and the price of electricity bought from the grid is 13 *p/kWh*. The operating cost of thermal storage is the maintenance costs. The capital recovery factor (F) is calculated from Eq. (22) and (12)% interest rate is applied for this case study.

$$F = \frac{r(1+r)^a}{(1+r)^a - 1} \tag{22}$$

6. Computational results

The proposed model has been implemented for 3 different microgrid scenarios:

1. *Basic scenario*: the microgrid is connected to the macrogrid; the electricity from the macrogrid is imported to meet the electricity demand within the scenario considered in addition to the electricity produced by the CHP generators. Moreover, when the

waste heat recovered from the CHP generators is larger than the heat demand of the site it can be dumped to the environment. Only one CHP technology is available to be selected for all sites, so the four CHP technologies are investigated separately under this scenario.

2. *Scenario 1*: the microgrid is connected to the macrogrid; the electricity from the macrogrid is imported to meet the electricity demand within the scenario considered in addition to the electricity produced by the CHP generators. When the waste heat recovered from the CHP generators is larger than the heat demand of the site it can be dumped to the environment. Multiple CHP technologies can be selected.
3. *Scenario 2*: the microgrid is connected to the macrogrid; the electricity from the macrogrid is imported to meet the electricity demand within the scenario considered in addition to the electricity produced by the CHP generators. When the waste heat recovered from the CHP generators cannot be dumped, so the CHP generators have to be designed to produce an amount of heat which is equal or lower than the heat demand of the site. Multiple CHP technologies can be selected.

Besides the above three scenarios, two alternative models are considered.

1. *Combined technologies*, each participant site in the microgrid can choose the CHP generators with any technology combination. The constraints are Eqs. (1)–(11), (14)–(18).
2. *Single technology*: each participant site in the microgrid can only choose one CHP technology, regardless the total capacity size. In this case, the constraints are Eqs. (1)–(18).

The developed MILP model is implemented using CPLEX 12.4.0.1 in GAMS 23.9 (www.gams.com) [62] on a PC with an Intel Core 2 Duo, 2.99 GHz CPU and 3.25 GB of RAM. Firstly, we compare the optimal results (GWP, AP, cost and heat dumping) from minimising each single objective under the Basic scenario with those obtained under the Reference scenario. Under the Reference scenario, the electricity is solely bought from the grid while the heat is provided by the condensing boiler (as described in Section 2). Then the proposed two alternative multi-objective models are implemented under the Scenario 1 and 2. The optimal results are illustrated with Pareto curves and the optimal designs of the microgrid, which includes the CHP selection, are analysed and discussed.

6.1. Basic scenario

The optimal results for the Basic scenario are shown in Fig. 3, where each group of values are scaled based on the maximum value within that group (normalised results). Under the Basic scenario, the PEM fuel cell generator has the lowest environmental impact (GWP, AP) with the lower cost. SOFC is the most expensive CHP generator, while its environmental impacts are quite low compared with the ICE and SE and the heat dumping is lower compared with the PEM fuel cell. The heat dumping from the ICE is the highest due to its high Heat to Power ratio, as shown in Table 5. There is no heat dumping for SE only, but its environmental impacts and cost are the highest among the CHP technologies.

Figs. 4 and 5 provide the GWP and AP hot spot analysis of the microgrid energy system (including all CHP generators and additional units): manufacturing phase, use phase (which includes the operation of the DERs and the supply of natural gas) and imported electricity from the grid to satisfy the electricity demand. The results are based on the total electricity demand of the participant sites. The GWP due to the manufacturing phase is very limited for all the micro CHP technologies investigated, being at the maximum the 6% of the total GWP (for the ICE). The use phase is responsible of the majority of the GWP generated by PEM, SOFC and ICE, which can provide almost all the electricity demand for the whole microgrid. Higher amount of imported electricity from the grid is needed for SE, due to its lower electrical efficiency compared with the fuel cells technology (PEM and SOFC). The higher GWP for the ICE and SE is mainly due to the fact that they are based on a combustion process (internal for ICE and external for SE, respectively) which produces higher CO_2 emissions, compared with the reforming processes and electrochemical conversion associated with the fuel cells.

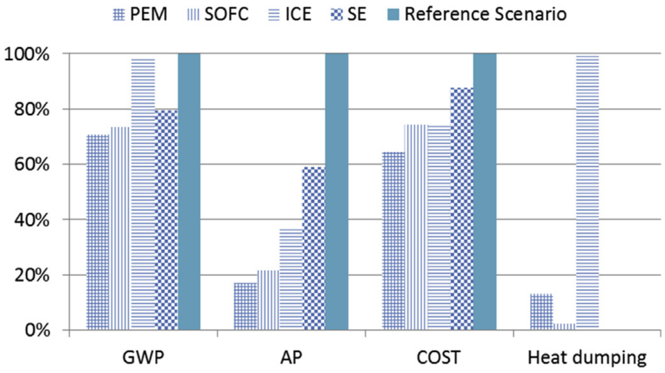

Fig. 3. Environmental impacts and cost for the basic scenario.

Fig. 5 illustrates the AP hot spot analysis for the Basic scenario. The AP impact category shows a larger gap between different technologies compared with the GWP, mainly due to the AP impact of the electricity imported from the grid. The total acidification impact is three times higher for the ICE compared with the PEM and SOFC generators. The contribution of the manufacturing phase to the total acidification impact is higher compared with the GWP for all the four micro CHP technologies, which means that the number of units installed in the microgrid becomes more relevant when the AP metric is considered in the optimisation model (see section 4.8.

When only cost and GWP are considered, the objective function is represented by the Eq. (20). The Pareto curves for EAC and GWP under the Basic scenario are shown in Fig. 6, together with the Pareto curves of Scenario 1 for both alternative models. Under the Basic scenario, PEM is the more suitable CHP technology for this microgrid, as shown also in Fig. 3. Meanwhile, the GWP of the PEM generator is lower than that of the other technologies. When only ICE or SE generators can be selected, more electricity needs to be imported from the grid to fulfil the electricity demand because of

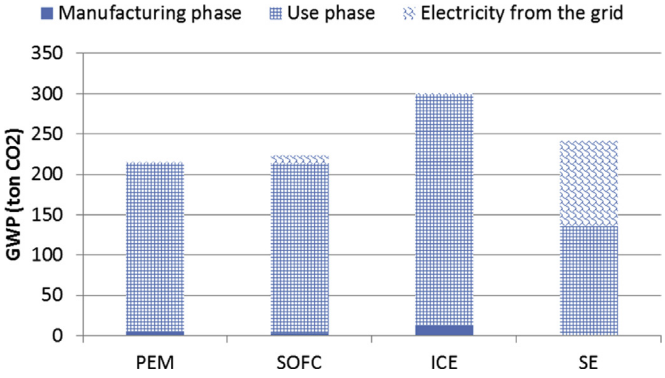

Fig. 4. GWP hotspot analysis for different micro CHP technologies.

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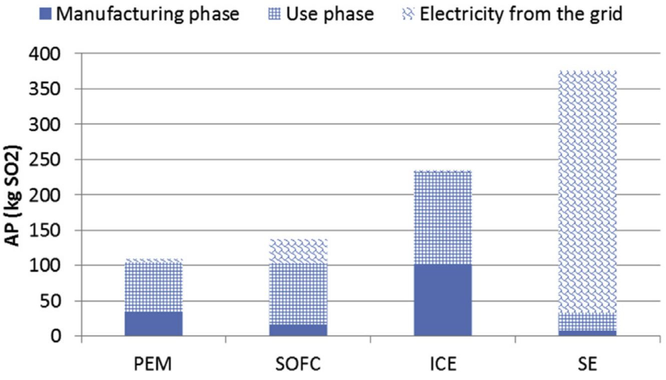

Fig. 5. AP hotspot analysis for different micro CHP technologies.

their high Heat to Power ratios, as shown in Fig. 4. This is reflected in their Pareto curves too as shown in Fig. 6. The obtained Pareto curves follow similar trend as the optimal results provided by Guo et al. [30], where the net present cost and the carbon dioxide emissions in the life cycle are the two objectives. If all technologies are available to be selected while each participant can select one technology at most (Scenario 1 – single technology), the total cost is even lower than that from PEM only and the GWP can be reduced by 5% compared with the PEM – Basic scenario. The GWP can be further reduced by about 3% when multiple technologies are selected (Scenario 1 – combined technologies). Compared with the reference scenario, excluding the manufacture phase, the GWP savings range between 30 and 37% while the EAC savings range between 10 and 34%. These values are comparable with those presented in the work of [28–30], which report values of 8%–39% for the CO_2 savings and 8%–29% for the economic savings.

6.2. Scenario 1 and scenario 2: comparison between single and combined technologies

Fig. 7 presents the Pareto curves for Scenario 1 and 2 for both alternative models. When heat dumping is forbidden (Scenario 2), the total cost increases since the model selects a CHP technology with lower heat to power ratio to avoid heat dumping which would be more expensive – i.e. PEM fuel cells and SOFC. In this scenario in fact the CHP has to be designed to satisfy the heat demand of the sites, and consequentially more electricity has to be imported from the grid. (see Fig. 13). When the single technology constraints are applied, the total cost predicted by the model is very similar to the case when the constraints are not applied (especially for Scenario 1). However, the GWP impacts are much smaller for the combined technology model compared to the single technology model under both scenarios.

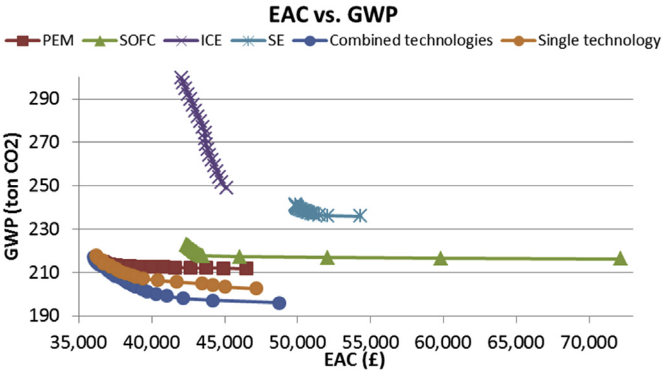

Fig. 6. Pareto curves for EAC and GWP of Basic scenario and Scenario 1.

Fig. 8 presents the selection of the capacity and the type of CHP technology for the combined technology model under Scenario 1. Results for the Scenario 2 have similar trend, so only Scenario 1 is provided. PEM is selected as the basic technology for both scenarios, while the others are selected as add-on generators. ICE is preferred only when there is loose constraint on the GWP under both scenarios. As GWP constraint becomes tighter, SOFC and SE are selected because of their lower GWP impacts compared with ICE.

Although multiple CHP technologies and capacities are selected at the same time, the utilisation rates for each technology are always between 30% and 80%. Fig. 9 provides the CHP utilisation rates for the combined technologies model for Scenario 1. At the last point (solution 21), the CHP generators are used between 20% and 55% of their capacities. This can be explained by the fact that when the GWP caps play a more important role, the sum of the single CHP capacity selected by the model increases (mainly due to SOFC and SE), which results in cost increasing. As the total GWP is driven by the use phase of the CHP generators, the utilisation factors are then lowered to keep the GWP at the minimum with higher capacities.

Figs. 10 and 11 show the total capacity selected for the condensing boiler and the thermal storage under both scenarios for both models. In general, when the single technology constraints are applied, the selected boiler capacity is higher than that of the combined technologies model. The single CHP generator selected by the site is not enough to provide the heat demand of the system while when multiple technologies are selected by the single site less boiler capacity is requested.

Figs. 12 and 13 show the total heat dumped during the year by the microgrid and the imported electricity from the grid, respectively. Heat dumping decreases as the GWP constraint becomes more important and it is lower for the combined technologies model compared to that of the single technology. Therefore, when multiple technologies are selected, the microgrid works in a more efficient way, i.e. exploiting better the energy produced internally by the CHP generators. As expected, more electricity is imported from the grid under Scenario 2 than Scenario 1, because heat dumping is not allowed under Scenario 2. Only a small amount of electricity is imported from the macrogrid under Scenario 1, while most electricity is provided locally by the CHP generators.

6.3. Cost vs. GWP and AP

When cost, GWP and AP are all considered, the objective of the optimisation model is represented by the Eq. (21). Only results for the combined technologies model are provided here. The Pareto curve for EAC and environmental factor under the two microgrid scenarios are shown in Fig. 14. The cost of the microgrid increases slowly as the environmental impact decreases for the first 11 points, while it increases more for the last 10 points under both

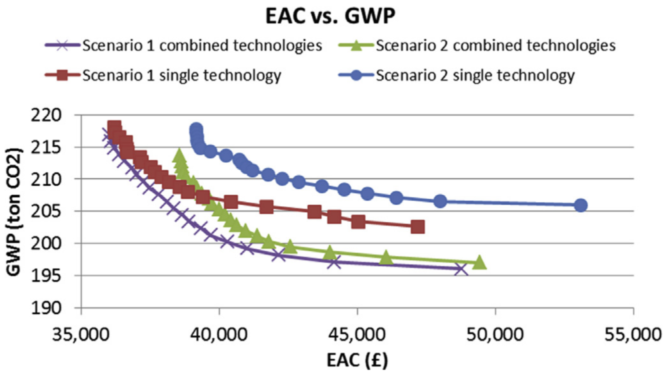

Fig. 7. Pareto curves for EAC and GWP of both scenarios.

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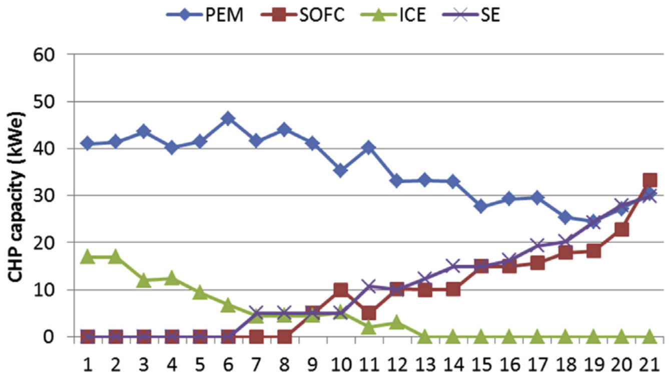

Fig. 8. CHP selections for EAC and GWP of Scenario 1.

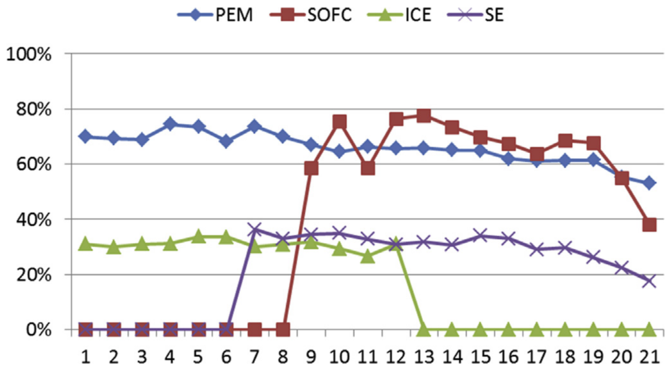

Fig. 9. CHP utilisation rate for EAC and GWP of Scenario 1.

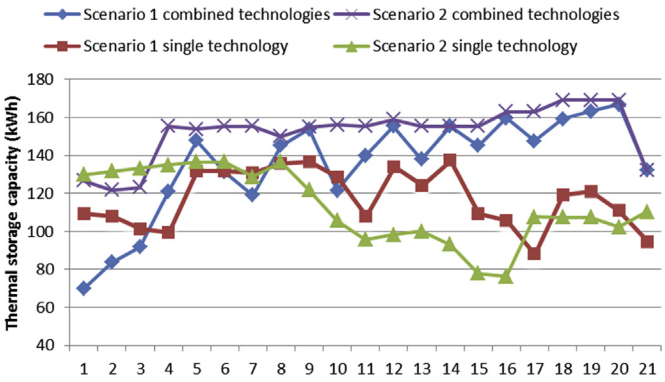

Fig. 11. Thermal storage selections for EAC and GWP of both scenarios.

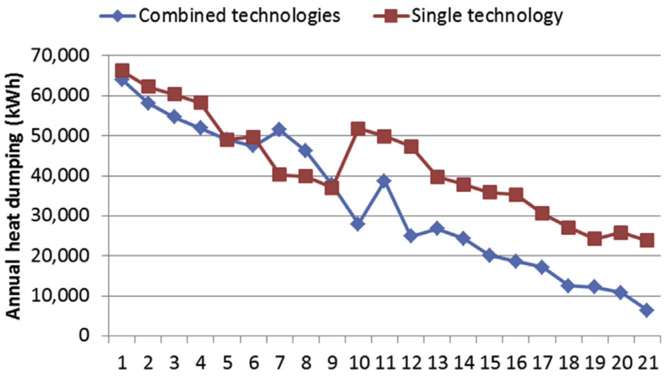

Fig. 12. Annual heat dumping for EAC and GWP of Scenario 1.

scenarios. However, the cost is higher when heat dumping is not allowed (Scenario 2) and the environmental impact is lower, following an opposite trend compared with the cost-GWP objective model.

Fig. 15 presents the selection of the technology and the capacity for the CHP generators on the given 20 intervals. PEM is again selected as the basic CHP technology for most points, while it is replaced by other technologies for the last two points.

CHP utilisation rates are presented in Fig. 16, showing a similar trend of the cost vs. GWP model (Fig. 9). However, when both AP and GWP are minimised (last point in the Pareto curve), the total capacity needed by the microgrid is lower compared with when GWP only is considered. Moreover only two technologies are selected when AP and GWP are considered (SOFC and SE), while in the cost-GWP model SOFC, SE and PEM are selected. This is because the utilisation rate at the final point is higher when AP and GWP are considered, showing a more efficient use of the available technologies.

7. Concluding remarks

The optimal design of microgrids with CHP generators has been addressed, through the development of an MILP model with multi-objective, using ε-constraint method. The model has considered both environmental and economic concerns. LCA methodology has been used to evaluate the environmental impacts of different microgrid designs which are then optimised based on economic metrics.

The proposed model is implemented on a case study with five participants of different building types. Three scenarios are

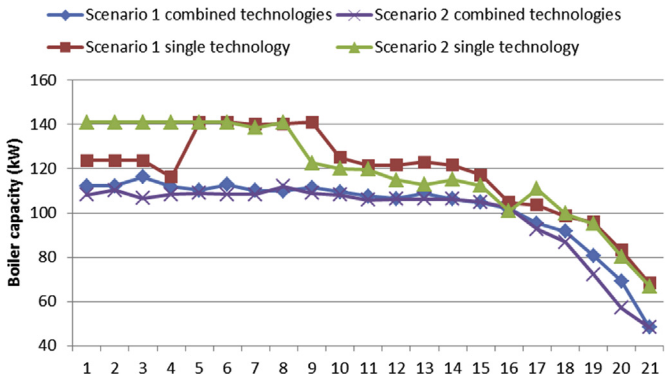

Fig. 10. Boiler selections for EAC and GWP of both scenarios.

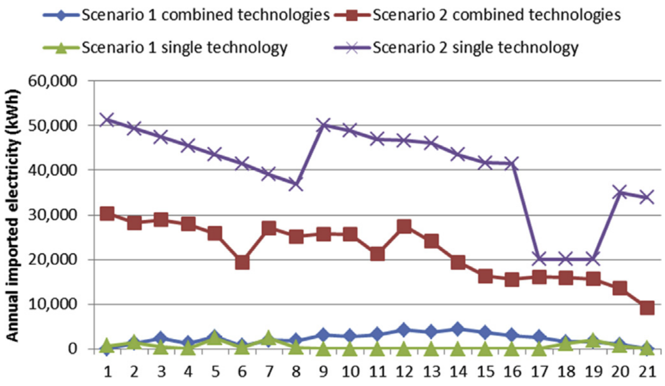

Fig. 13. Annual imported electricity for EAC and GWP.

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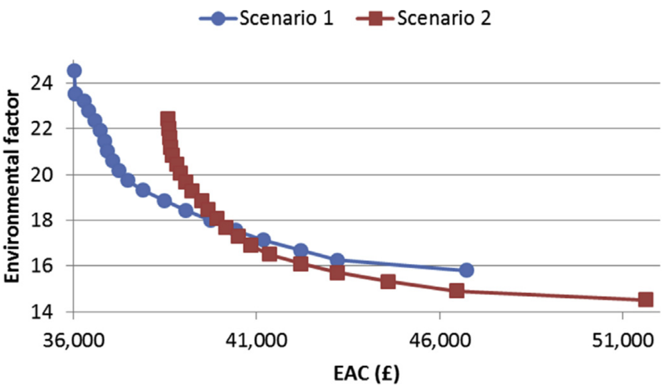

Fig. 14. Pareto curves for EAC and environmental factor of both scenarios for the combined technologies model.

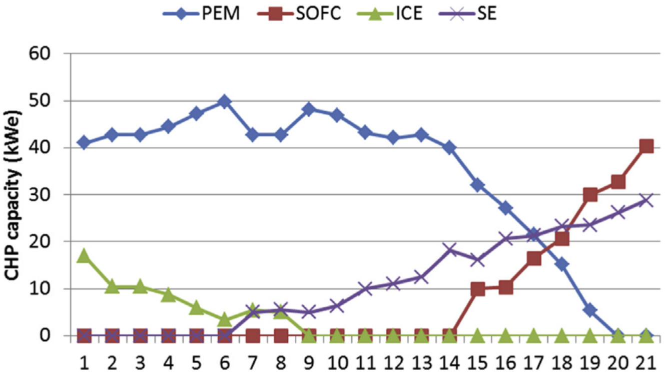

Fig. 15. CHP selections for EAC and environmental factor of Scenario 1.

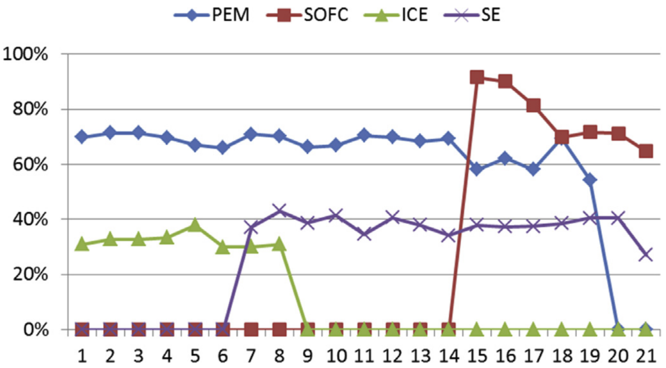

Fig. 16. CHP utilisation rate for EAC and environmental factor of Scenario 1.

considered with two different models. The results of this paper show that a microgrid with multiple CHP technologies represents a less expensive and more environmentally friendly solution for a group of different users. The decision makers can select their preferred CHP-based microgrid design from the obtained Pareto-optimal solutions.

Optimal designs based on the selection of four CHP technologies have been compared, based on the three objectives which minimise the EAC, the GWP and the AP. The GWP impact of the manufacturing phase gives a nugatory contribution to the total GWP, which is mainly dominated by the use phase of the CHP unit. On the other hand, the AP impact of the manufacturing phase plays a more important role on the total AP impact, which means that the selection of the number of CHP generators per site is influenced more by the AP impact than the GWP. A lower total CHP capacity is selected when GWP and AP are both considered, with higher utilisation factors.

The results have shown that the selection of multiple technologies obtains lower cost with higher environmental saving compared with the Basic scenario and the single technology model, meaning that when multiple technologies are selected the microgrid works in a more efficient way, i.e. exploiting better the energy produced internally by the CHP generators.

The work of Mallikarjun and Lewis [1] indicated that fuel cells are mostly suitable for electric needs because of their high electric efficiency and low heat to power ratios. In our work, a PEM fuel cell is chosen as the basic CHP technology for most solutions, providing both electricity and heat, because it offers lower environmental impacts at low cost. Meanwhile, ICE and SE are preferred if the heat demand is high, as for some of the scenarios analysed. This work demonstrates that the selection of DERs depends heavily on the heat and electricity profiles of the assumed participants. Finally, it implies that CHP selection is influenced by the characteristics of the CHP units assumed in this study. Amongst them, the electrical and thermal efficiencies play an important role, especially for the PEM fuel cell, SOFC and SE which are still far away from a fully marketable state.

The proposed model is based on assumptions which may need further consideration in future. Firstly, the CHPs are assumed to have constant efficiency under all conditions, although this depends on the load factor. Secondly, the heat loss of the thermal energy storage as a function of time length has not been considered in this study and may have to be considered in future analysis. Thirdly, a future analysis may consider the option of selling electricity back to the grid. Fourthly, in the present study, the GWP and AP impact factors are collected from the UK data base which is based on the current electricity production technology mix. The model may be improved in the future to include green technology, such as wind generator and solar panels, for electricity production. Finally, future work may also consider the sensitivity analysis of the CHP characteristics on the microgrid design, e.g. the electrical efficiency and the heat to power ratio.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2015.03.036.

References

[1] Mallikarjun S, Lewis HF. Energy technology allocation for distributed energy resources: a strategic technology-policy framework. Energy 2014;72:783–99.

[2] Utilyx. Coming of age - decentralised energy? p. 1–32. [Online] Available: http://www.utilyx.com/documents/pdf/realisingthestrategicpotencialofonsitegeneration.pdf.

[3] Jones P. Decentralised Energy business opportunity in resource efficiency and carbon management. 2008. p. 1–30 [Online] Available: http://www.ecolateral.org/decentralised-energy-business-opportunity-in-resource-efficiency-and-carbon-management/.

[4] Basak P, Chowdhury S, Halder nee Dey S, Chowdhury SP. A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid. Renew Sustain Energy Rev 2012;16:5545–56.

[5] DECC. Microgeneration strategy. 2011 [Online] Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48114/2015-microgeneration-strategy.pdf.

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[6] International Energy Agency. Combined heat and power: evaluating the benefits of greater global investment. 2008. p. 1–39 [Online] Available: http://www.iea.org/publications/freepublications/publication/chp_report.pdf.

[7] Evangelisti S, Lettieri P, Clift R, Borello D. Distributed generation by energy from waste technology: a life cycle perspective. Process Saf Environ Prot 2014;93:161–72.

[8] Kopanos GM, Georgiadis MC, Pistikopoulos EN. Energy production planning of a network of micro combined heat and power generators. Appl Energy 2013;102:1522–34.

[9] Pehnt M. Environmental impacts of distributed energy systems—The case of micro cogeneration. Environ Sci Policy 2008;11:25–37.

[10] Guy R, Sykes B. Micro CHP accelerator - final report. Carbon Trust; 2011. p. 1–56 [Online] Available: http://www.carbontrust.com/resources/reports/technology/micro-chp-accelerator.

[11] Micro CHP report powers discussion on UK energy future. Fuel Cells Bull 2013;2013:3–4.

[12] Marnay C, Venkataramanan G, Stadler M, Siddiqui A, Firestone R, Chandran B. Optimal technology selection and operation of microgrids in commercial buildings. IEEE Trans Power Syst 2008;23:975–82.

[13] Asano H, Bando S, Watanabe H. Methodology to design the capacity of a microgrid. In: Proceeding of the ieee international conference on system of systems engineering, San Antonio, TX; 2007. p. 1–6.

[14] Zhang Y, Mao M, Ding M, Chang L. Study of energy management system for distributed generation systems. In: Proceeding of IEEE third international conference on electric utility deregulation and restructuring and power technologies,Nanjuing; 2008. p. 2465–9.

[15] Obara S. Equipment arrangement planning of a fuel cell energy network optimized for cost minimization. Renew Energy 2007;32:382–406.

[16] Mehleri ED, Sarimveis H, Markatos NC, Papageorgiou LG. A mathematical programming approach for optimal design of distributed energy systems at the neighbourhood level. Energy 2012;44:96–104.

[17] Basu AK, Chowdhury S, Chowdhury SP. Strategic deployment of CHP-based distributed energy resources in microgrids. In: Power & energy society general meeting, Calgary, AB; 2009. p. 1–6.

[18] Logenthiran T, Srinivasan D, Khambadkone AM, Sundar Raj T. Optimal sizing of distributed energy resources for integrated microgrids using evolutionary strategy. In: Congress on evolutionary computation (CEC), Brisbane; 2012. p. 1–8.

[19] Zhang D, Samsatli NJ, Hawkes AD, Brett DJL, Shah N, Papageorgiou LG. Fair electricity transfer price and unit capacity selection for microgrids. Energy Econ 2013;36:581–93.

[20] Hawkes AD, Leach MA. Modelling high level system design and unit commitment for a microgrid. Appl Energy 2009;86:1253–65.

[21] Obara Sy, Watanabe S. Optimization of equipment capacity and an operational method based on cost analysis of a fuel cell microgrid. Int J Hydrogen Energy 2012;37:7814–30.

[22] Sheikhi A, Ranjbar AM, Oraee H. Financial analysis and optimal size and operation for a multicarrier energy system. Energy Build 2012;48:71–8.

[23] Basu AK. Microgrids: planning of fuel energy management by strategic deployment of CHP-based DERs – an evolutionary algorithm approach. Int J Electr Power Energy Syst 2013;44:326–36.

[24] Alonso M, Amaris H, Alvarez-Ortega C. Integration of renewable energy sources in smart grids by means of evolutionary optimization algorithms. Expert Syst Appl 2012;39:5513–22.

[25] Bhumkittipich K, Phuangpornpitak W. Optimal Placement and sizing of distributed generation for power loss reduction using particle swarm optimization. Energy Procedia 2013;34:307–17.

[26] Fu Q, Solanki A, Montoya LF, Nasiri A, Bhavaraju V, Abdallah T, et al. Generation capacity design for a microgrid for measurable power quality indexes. Washington, DC: Innovative Smart Grid Technologies; 2012. p. 1–6.

[27] Bando S, Asano H, Sasajima K, Odajima N, Sei M, Ogata T. Optimal configuration of energy supply system in a microgrid with steam supply from a municipal waste incinerator. In: 8th international conference on power electronics and ECCE Asia, Jeju; 2011. p. 557–64.

[28] Cardoso G, Stadler M, Bozchalui MC, Sharma R, Marnay C, Barbosa-Póvoa A, et al. Optimal investment and scheduling of distributed energy resources with uncertainty in electric vehicle driving schedules. Energy 2014;64:17–30.

[29] Mizani S, Yazdani A. Optimal design and operation of a grid-connected microgrid. In: Electrical power & energy conference, Montreal, QC; 2009. p. 1–6.

[30] Guo L, Liu W, Cai J, Hong B, Wang C. A two-stage optimal planning and design method for combined cooling, heat and power microgrid system. Energy Convers Manag 2013;74:433–45.

[31] Clift R. System approaches: life cycle assessment and industrial ecology [Chapter 17]. In: Harrison RM, editor. Pollution: causes, effects and control. 5th ed. London: Royal Society of Chemistry; 2013.

[32] Manfredi S, Pant R. Improving the environmental performance of bio-waste management with life cycle thinking (LCT) and life cycle assessment (LCA). Int J Life Cycle Assess 2013;18(1):285–91.

[33] Clift R, Doig A, Finnveden G. The application of life cycle assessment to integrated solid waste management. Process Saf Environ Prot 2000;78:279–87.

[34] ISO. ISO 14040: environmental management – life cycle assessment – Principles and framework. Geneva. 2006 [Online] Available:, http://www.iso.org/iso/catalogue_detail?csnumber=37456.

[35] Hawkes AD, Aguiar P, Croxford B, Leach MA, Adjiman CS, Brandon NP. Solid oxide fuel cell micro combined heat and power system operating strategy: options for provision of residential space and water heating. J Power Sources 2007;164:260–71.

[36] Giannopoulos D, Founti M. Parametric comparative analysis of lifetime energy demand and CO_2 -eq savings of a SOFC m-CHP unit. Lucerne: European Fuel Cell Forum; 2011. p. 1–21.

[37] Staffell I, Ingram A, Kendall K. Energy and carbon payback times for solid oxide fuel cell based domestic CHP. Int J Hydrogen Energy 2012;37:2509–23.

[38] Halliday J, Peters M, Powell J, Peters M. Fuel cells: providing heat and power in the urban environment. Tyndall Centre Technical Report 32. 2005 [Online] Available:, http://www.tyndall.ac.uk/content/fuel-cells-providing-heat-and-power-urban-environment.

[39] Jing Y-Y, Bai H, Wang J-J. Multi-objective optimization design and operation strategy analysis of BCHP system based on life cycle assessment. Energy 2012;37:405–16.

[40] Bernier E, Maréchal F, Samson R. Multi-objective design optimization of a natural gas-combined cycle with carbon dioxide capture in a life cycle perspective. Energy 2010;35:1121–8.

[41] Lo Prete C, Hobbs BF, Norman CS, Cano-Andrade S, Fuentes A, von Spakovsky MR, et al. Sustainability and reliability assessment of microgrids in a regional electricity market. Energy 2012;41:192–202.

[42] Ristimäki M, Säynäjoki A, Heinonen J, Junnila S. Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. Energy 2013;63:168–79.

[43] Pieragostini C, Mussati MC, Aguirre P. On process optimization considering LCA methodology. J Environ Manag 2012;96:43–54.

[44] Chao D, Zhaohui L, Xinyu S, Chaoyong Z. Integration and optimization of LCA and LCC to eco-balance for mechanical product design. In: 7th world congress on Intelligent control and automation. Chongqing; 2008. p. 1085–90.

[45] Antipova E, Boer D, Guillén-Gosálbez G, Cabeza LF, Jiménez L. Multi-objective optimization coupled with life cycle assessment for retrofitting buildings. Energy Build 2014;82:92–9.

[46] Lira-Barragán LF, Ponce-Ortega JM, Serna-González M, El-Halwagi MM. Optimal design of process energy systems integrating sustainable considerations. Energy 2014;76:139–60.

[47] Jolai F, Neyestani MS, Golmakani H. Multi-objective model for multi-period, multi-products, supplier order allocation under linear discount. Int J Manag Sci Eng Manag 2013;8:24–31.

[48] Eriksson O, Finnveden G, Ekvall T, Björklund A. Life cycle assessment of fuels for district heating: a comparison of waste incineration, biomass- and natural gas combustion. Energy Policy 2007;35:1346–62.

[49] BSI 2011. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services (PAS 2050). 2011. London.

[50] Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R. Life cycle assessment. An operational guide to the ISO standards. 2001. p. 1–19. Leiden.

[51] Ecoinvent. Ecoinvent V.2.0. 2011 [Online]. Available: http://www.ecoinvent.org/.

[52] PE International. GaBi sustainability software. 2013 [Online]. Available: http://www.gabi-software.com/uk-ireland/software/gabi-software/.

[53] Hawkes AD, Brett DJL, Brandon NP. Fuel cell micro-CHP techno-economics: Part 1-model concept and formulation. Int J Hydrogen Energy 2009;34:9545–57.

[54] Hawkes AD, Brett DJL, Brandon NP. Fuel cell micro-CHP techno-economics: Part 2-Model application to consider the economic and environmental impact of stack degradation. Int J Hydrogen Energy 2009;34:9558–69.

[55] Weber C, Shah N. Optimisation based design of a district energy system for an eco-town in the United Kingdom. Energy 2011;36(2):1292–308.

[56] Shaneb OA, Coates G, Taylor PC. Sizing of residential μCHP systems. Energy Build 2011;43:1991–2001.

[57] Staffell I, Green R. The cost of domestic fuel cell micro - CHP systems. London. 2012. p. 1–24 [Online].Available:, https://spiral.imperial.ac.uk/bitstream/10044/1/9844/6/Green%202012-08.pdfp.

[58] James BD, Spisak AB, Colella WG. Cost estimates of stationary fuel cell systems. Strategic Analysis; 2012 [Online]. Available: http://www.fuelcellseminar.com/media/51164/sta32-2.pdf.

[59] Hybrid energy systems in future low carbon buildings. University of Strathclyde; 2014 [Online]. Available: http://www.esru.strath.ac.uk/EandE/Web_sites/09-10/Hybrid_systems/intro.htm.

[60] The future of natural gas appendix 5C: commercial and residential applications of combined heat and power, an Interdisciplinary MIT study. 2011 [Online]. Available: https://mitei.mit.edu/system/files/NaturalGas_Appendix5C.PDF.

[61] Berliner Energieagentur GmbH. Study “Use of micro CHP units in the electrical power range 1 – 5 kWe for Berlin“. 2007 [Online]. Available: http://www.cres.gr/perch/Germany1.htm.

[62] Brooke A, Kendrick D, Meeraus A, Raman R. GAMS - a user's guide. 2008.

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