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Optimal online operation of residential μCHP systems using linear programming

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ABSTRACT

Environmental pressures have resulted in an increased importance being placed on the efficient production and consumption of energy. Micro combined heat and power (μCHP) technology has the potential to make an important contribution to make the transition to more sustainable energy systems since it is a highly efficient technology for generating both electricity and heat from a single fuel source. The conventional operation strategies for these technologies are pre-determined and either heat-led or electricity-led. This paper presents an optimal online operation strategy for μCHP systems, which is more efficient than the aforementioned conventional pre-determined operation strategies. A generic optimal online linear programming (LP) optimiser has been developed for operating a μCHP system. It is generic since it is applicable for any μCHP technology or demand profile. This optimiser is capable of minimising the daily operation costs of such a system. Three different simulation scenarios have been investigated: the new feed-in tariff (FIT) scheme; the trade of electricity; the introduction of a carbon tax. In all three investigated scenarios, the results show that the optimiser significantly reduces operation costs when compared to the conventional pre-determined operation strategies. As such, it is suggested that the optimiser has the potential to deliver significant energy savings in practice.

1. Introduction

International drives towards increased energy efficiency have led to increased interests in μCHP technologies since they have the potential to deliver both electricity and heat from a single fuel source in a highly efficient manner. Many companies are developing this technology for residential applications based on either an internal combustion engine (ICE), a Stirling engine (SE) or a fuel cell (FC) [1]. For instance, Ceres Power is developing a 1.0 kWe solid oxide fuel cell that is expected to be ready for mass production by the middle of 2011 [2].

Recent research conducted by the authors [3] has shown that relying on a single strategy for the operation of a μCHP system is not always the optimum choice whereas a hybrid strategy could achieve improved performance, which could save approximately €150 per year. Furthermore, it is well known that both residential electricity and heat demands fluctuate daily and seasonally, which makes the use of a pre-determined operation strategy less beneficial due to not being responsive to such dynamic fluctuations. For example, using an electricity-led strategy could lead to a waste of heat when there is little heat demand and the thermal storage device is fully charged. Instead, using an appropriate optimal online operation strategy, which aims for the most efficient operation of the μCHP system, is expected to outperform conventional operation strategies [1]. As a result, this study is concerned with developing an effective tool for optimal operation of residential μCHP systems.

LP techniques are principally used for determining the best allocation of limited resources either by maximising the profits or minimising the costs [4]. These techniques, which have the advantage of rapid calculation even with large problems containing a significant number of variables and constraints, are widely used for solving decision making problems. Conversely, in non-linear programming, the significant number of variables makes solving the problem more difficult and time consuming [5,6].

LP has been used for the optimisation of energy systems with different purposes and applications as summarised in Table 1.

Previous research has not developed a generic online LP optimiser for residential μCHP systems that accounts for a back-up heater and thermal storage device. In addition, the influence of some emerging energy policies, such as FIT and carbon tax, has not yet been considered. In this paper, a generic optimal online LP model for the operation of a μCHP system, which is named 'optimiser', is presented and has been developed, using the Matlab [13]. It has been formulated in a generic form to allow its use for any μCHP system and any demand profile. Importantly, in contrast to earlier work related to single run optimisation to determine the size of μCHP systems [4], this optimiser operates continuously online

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Table 1
Summary of CHP applications investigated using LP.

CHP application investigated using LP
1. Sizing of μCHP systems [4]
2. High-level system design and unit commitment of a micro grid (μG) [7]
3. Optimising the decision-making to manage CHP systems [8]
4. Determining the optimal strategies of a gas turbine-based CCHP system [9]
5. Studying the effect of fuel price on cost-minimised operation of CHP plants [10]
6. Evaluating the influence of uncertainties in energy demands on the optimal size of a FC-based CHP system used for an office building [11]
7. Optimising the CHP system for industrial sites [12]

with the aim of optimising the efficient operation of the μCHP system. Further, the developed online optimiser minimises the daily operation costs (c_{DO}) of such a system. Uncertainties in electrical and thermal demands have been considered by generating random errors for each individual value. Three simulation scenarios with different incentive mechanisms for installing μCHP technologies have been investigated: the FIT scheme recently adopted in the UK [14]; the trade of electricity; the introduction of a carbon tax. Sensitivity analyses have been performed to gain an understanding of the influence of key parameters on decision making regarding the operation of residential μCHP systems.

The remainder of this paper is organised as follows. Section 2 describes the conventional pre-determined operation strategies for μCHP systems. In Section 3, an online LP optimiser is presented and developed for online operation of μCHP systems. Section 4 presents results and a discussion based on the savings achieved through the application of the developed online LP optimiser in three different simulation scenarios. Finally, Section 5 draws conclusions regarding the strategies and the implications of the results obtained.

2. Conventional operation strategies for μCHP systems

An operation strategy for μCHP systems is a strategy for activating, deactivating or turning down/up the μCHP unit. In other terms, an operation strategy is the way of operating the μCHP unit and managing the flow of thermal and electrical energy within and to/from the system. The operation strategy aims to achieve specific targets, beneficial to the householder. Consequently, the operation strategy of a μCHP system has to answer the following important timing questions taking into consideration the need to achieve certain goals [1]:

- When should the μCHP unit be activated/deactivated/turned down/ramped up or ramped down?
- When should the thermal storage device be charged/discharged and at what rate?
- When should the back-up heater be switched on/off?
- When should electricity be exported/imported and how much?

These questions are difficult to answer since operating the system is complex due to a range of factors: different μCHP units and different sizes for each type with different thermal and electrical outputs; energy losses from both electrical and thermal storage devices to be considered; seasonal and in-seasonal variation in thermal and electrical demands according to climate, occupants and type of building; variation in prices of gas, imported and exported electricity; technical constraints of operating the μCHP unit and other components of the system such as ramp-up and ramp-down rates [1].

There are several operation strategies described in existing literature [1]. However, heat-led and electricity-led operation strategies are the prominent operation strategies for residential μCHP technologies available in the market [1].

2.1. Heat-led strategy

This operation strategy is based on meeting thermal demand by operating the μCHP unit and then meeting any deficiency with a back-up heater [15,16]. Technical constraints should be considered during the operation of the system such as the ability for modulation to meet low heat demands. This operation strategy is the most prominent for operating the μCHP units available in the market, especially SEs since they have a high heat to power ratio [17]. However, when a heat-led operation strategy is used, a substantial amount of electricity will be exported during periods of high heat demand and low electrical demand. As a result, electricity would be exported even when the exporting price is not profitable [18].

2.2. Electricity-led strategy

This operation strategy is based on operating the μCHP unit, within the operating limits, to meet the maximum possible amount of the electrical demand while any deficiency can be imported from the μG [19]. The same strategy may also be implemented to meet the needs of the electricity supplier [20] by operating the μCHP unit via a smart meter for certain periods. The system in this strategy should be integrated with a thermal storage unit to store heat when there is no thermal demand or when thermal demand is less than the produced heat. In addition, it should also be integrated with a back-up heater to compensate any deficiency in meeting the thermal demand [15].

3. Online operation of μCHP systems using linear programming

3.1. Overview

The residential μCHP system consists of a μCHP unit, a thermal storage device and a back-up heater. The μCHP unit, which is driven by natural gas, is used to meet the electrical and heat demands. However, when the amount of electrical output from the μCHP unit is greater than the demand, the surplus electricity can be exported to the micro grid (μG). Conversely, the μG can supply the dwelling with any deficit in electricity. Any excess heat will be diverted to the thermal storage device and used when it is needed. However, if the thermal output does not satisfy the demand and there is not enough stored heat, a back-up heater is used. Fig. 1 shows the conceptual arrangement of the residential μCHP system, which includes a μCHP unit, a thermal storage device and a back-up heater and is integrated within a μG.

In this study, the operation of a residential μCHP system is formulated as an online optimisation LP model (LP optimiser) as described in the following sections. The optimiser is formulated in a generic form to allow its use for any μCHP system and any demand pattern.

3.2. Model assumptions

The main purpose of the model is to optimally operate a residential μCHP system, where the electrical output of the μCHP unit is daily determined on an hourly basis. As such, the model involves determining optimal values for 24 decision variables: the hourly electrical output of the μCHP unit (kWe) for a whole day. These decision variables will be determined according to an objective function to minimise c_{DO}.

It is assumed that the μCHP unit can operate anywhere between 0% and 100% of its capacity. In addition, the μCHP system is assumed

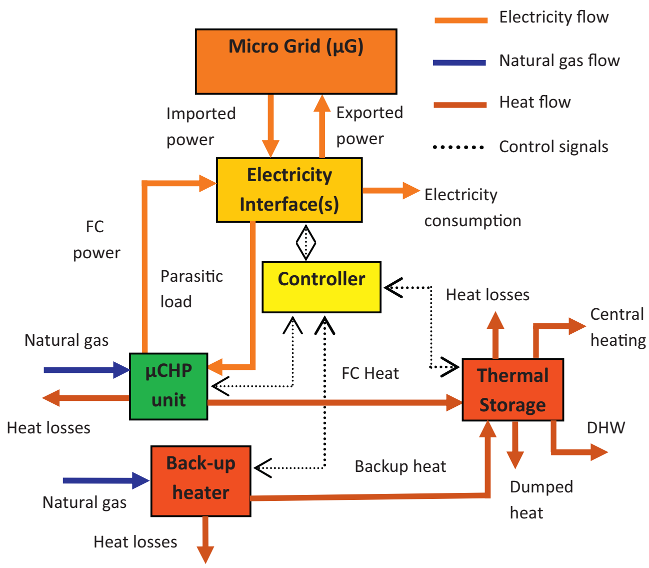

Fig. 1. A conceptual arrangement of residential μCHP system [1].

to be perfectly reliable, i.e., shutdowns are not considered in the model.

The required input values for the model are:

1. Maintenance costs of both μCHP unit and back-up heater, $m_{\mu\text{CHP}}$, m_B, respectively (€/kWh)
2. Prices of natural gas and imported electricity, c_{NG}, γ, respectively (€/kWh)
3. FIT for both generated and exported electricity, FIT_G, FIT_{ex}, respectively (€/kWh)
4. Forecasted hourly end-use electricity and heat demands, L_j, H_j, respectively (kWh)
5. Electrical and thermal efficiencies of the μCHP unit, η_e, η_{th}, respectively.
6. Efficiency of the back-up heater, η_B
7. Round-trip efficiency of the thermal storage device, η_s
8. Carbon tax, t_C (€/tonne of CO_2)

All the above input values have been considered constants in the developed online operation model. However, the values of forecasted hourly end-use electricity demand (L_j) and heat demand (H_j) have been estimated to vary within 10% of actual values [21]. Consequently, each single value of heat or electricity demand can vary from 90% to 110% of the actual demand.

The model determines the following two outputs:

1. Electrical output of μCHP unit for 24 h, $o_{el,i}$ (kWe)
2. Minimum c_{DO} for meeting electricity and heat demands (€)

3.3. Mathematical formulation

Online operation of a residential μCHP system has been formulated as an LP minimisation model. The model is named optimiser; Fig. 2 shows an overview of this optimiser. In order to follow the notation used hereafter, the reader is directed to the nomenclature in Appendix A.

3.3.1. Decision variables

The model contains six types of operation variables:

- the electrical output of the μCHP unit during the *i*th hour ($o_{el,i}$) (kWh)
- the thermal output of the backup heater during the *i*th hour ($o_{th,i}$) (kWh)
- the exported electricity during the *i*th hour ($o_{ex,i}$) (kWh)
- the imported electricity during the *i*th hour ($o_{im,i}$) (kWh)
- the thermal input to the storage device during the *i*th hour ($o_{st\_in,i}$) (kWh)
- the thermal output from the storage device during the *i*th hour ($o_{st\_out,i}$) (kWh)

The number of variables is the product of the number of operation variables and the number of hours per day, i.e. 144 (6 × 24).

The value of $o_{el,i}$ can vary from 0 kWh to the maximum possible electrical output of the μCHP unit while the value of $o_{th,i}$ can vary from zero to the maximum possible output of the back-up heater. The value of $o_{ex,i}$ can vary from zero when no exporting occurs to the maximum possible electrical output of the μCHP unit when there is no demand at all. The value of $o_{im,i}$ can vary from zero when it is more desirable to cover all the electrical demand from the μCHP unit to the highest possible value of demand, which vary from one dwelling to another. The value of $o_{st\_in,i}$ can vary from 0 kWh to the value of thermal output of the μCHP unit when there is no heat demand while the value of $o_{st\_out,i}$ vary from zero when the μCHP unit is able to over heat demand to the maximum value that the storage device can deliver when there is no heat output from the μCHP unit.

3.3.2. Objective function

The objective of the optimiser is to minimise c_{DO}, which is the sum of daily operation costs for operating the μCHP system, while meeting both electricity and heat demands, taking technical and operational constraints into consideration. It includes the daily costs of imported electricity, fuel and maintenance, minus the revenue from the FIT for generation and exporting of electricity. As a result, the objective function can be expressed as follows:

$$\min \quad c_{DO} = \sum_{i=1}^{n_h} (\alpha o_{el,i}) + (\beta o_{th,i}) + (\gamma o_{im,i}) - (\delta o_{ex,i}) + (\varepsilon o_{st\_in,i}) - (\xi o_{st\_out,i}) \quad (1)$$

The coefficients α, β, γ, δ, ε and ξ can be calculated as follows:

$$\alpha = \left(\frac{c_{NG} + e_{NG} \times t_C}{\eta_e}\right) \times \left(\frac{\text{HHV}}{\text{LHV}}\right) + m_{\mu\text{CHP}} \quad (2)$$

$$\beta = \left(\frac{c_{NG} + e_{NG} \times t_C}{\eta_B}\right) \times \left(\frac{\text{HHV}}{\text{LHV}}\right) + m_B \quad (3)$$

$$\gamma = c_{Eimp} + (e_{Grid} \times t_C) \quad (4)$$

$$\delta = c_{Eexp} + (e_{Grid} \times t_C) \quad (5)$$

$$\varepsilon = \alpha \times Q \times \eta_e \quad (6)$$

$$\xi = \frac{\alpha \times Q \times \eta_e}{\eta_s} \quad (7)$$

3.3.3. Constraints

The constraints imposed on the developed LP optimiser are as follows:

- The inability of a μCHP unit, a thermal storage and a back-up heater to exceed their maximum ratings:

$$o_{el,i} - R_{CHP} \le 0 \quad \text{for} \quad i = 1\text{–}24 \quad (8)$$

$$o_{th,l} - R_B \le 0 \quad \text{for} \quad i = 1\text{–}24 \quad (9)$$

$$o_{st\_in,i} - R_S \le 0 \quad \text{for} \quad i = 1\text{–}24 \quad (10)$$

$$o_{st\_out,i} - R_S \le 0 \quad \text{for} \quad i = 1\text{–}24 \quad (11)$$

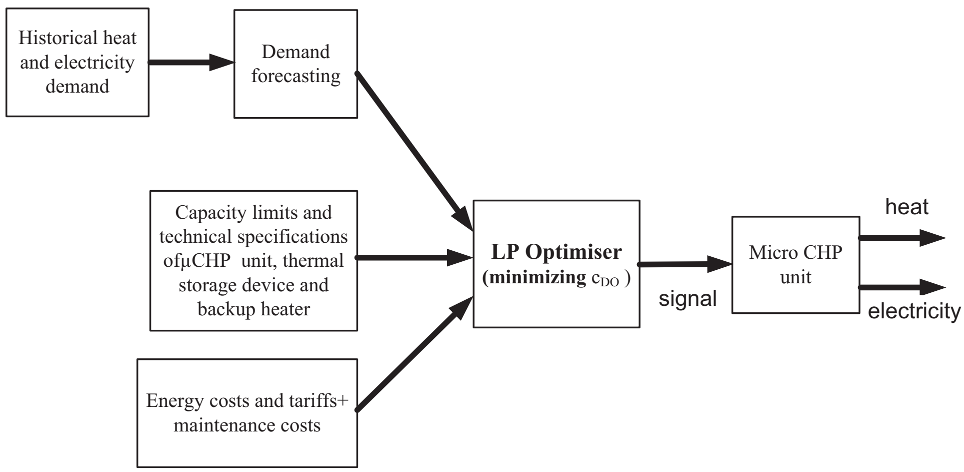

Fig. 2. Overview of the LP optimiser.

- The output from the thermal storage device cannot exceed the amount of thermal energy stored plus the thermal energy absorbed by the thermal storage device each hour.

$$o_{\mathrm{st_{out}},i} \le o_{\mathrm{st\_in},i} + \sum_{i=1}^{24}(o_{\mathrm{st\_in},i} - o_{\mathrm{st\_out},i}) \qquad (12)$$

- The input to the storage device cannot exceed the difference between the capacity of the thermal storage device and the amount of energy stored plus the energy exported from the storage device each hour.

$$o_{\mathrm{st_{in}},i} \le R_{\mathrm{S}} - \sum_{i=1}^{24}(o_{\mathrm{st\_in},i} - o_{\mathrm{st\_out},i}) + o_{\mathrm{st\_out},i} \qquad (13)$$

- Ramp limits for the µCHP unit cannot be exceeded. Ramp limits are the ability of the PEMFC to ramp up and ramp down from a steady state operating position. Experimental data has shown that a 1 kWe PEMFC cannot ramp up at a faster rate than 41.67 We/min and cannot ramp down at a faster rate than 50 We/min [22]. The same ramp rate, expressed as a percentage of the kWe rating, is used for the 2 kWe PEMFC. This means that a 2 kWe PEMFC cannot ramp up at a faster rate than 83.34 We/min and cannot ramp down at a faster rate than 100 We/min. These values have been included in the model as follows:

$$o_{\mathrm{el},i} - o_{\mathrm{el},i+1} \le R_{\mathrm{d}} \quad \text{for} \quad i = 1\text{–}24 \qquad (14)$$

$$o_{\mathrm{el},i+1} - o_{\mathrm{el},i} \le R_{\mathrm{u}} \quad \text{for} \quad i = 1\text{–}24 \qquad (15)$$

- Forecasted electricity demand of the house each hour (L_i) must be met exactly. However, importing and exporting electricity from/to the µG is possible.

$$o_{\mathrm{el},i} + o_{\mathrm{im},i} - o_{\mathrm{ex},i} = L_i \quad \text{for} \quad i = 1\text{–}24 \qquad (16)$$

- Forecasted heat demand (H_i) must be met exactly and no heat dumping is allowed.

$$o_{\mathrm{el},i} \times Q + o_{\mathrm{th},i} - o_{\mathrm{st\_in},i} + o_{\mathrm{st\_out},i} = H_i \quad \text{for} \quad i = 1\text{–}24 \qquad (17)$$

where Q is the heat to power ratio of the µCHP unit.

The number of inequality constraints generated from the eight expressions (8)–(15), is the product of the number of expressions and the number of hours per day, i.e. 168 (8 × 24). Similarly, the number of inequality constraints generated from the two expressions: (16) and (17) is 48 (2 × 24).

4. Results and discussion

In order to test the developed online LP optimiser, three simulation scenarios have been investigated to establish how the µCHP unit operates and quantify its associated operating costs. The investigations represent a comparison between the optimiser and the conventional pre-determined operation strategies (heat-led and electricity-led) for all three scenarios. The results obtained by the online LP model are used as input signals to a model of µCHP system, which was previously developed by the authors [3]. The model is capable of simulating the performance of a µCHP system for any period of time. This µCHP system consists of the following components: one µCHP unit, one back-up heater, one thermal storage device and a µG connection to allow importing and exporting of electricity, as previously illustrated in Fig. 1.

4.1. Feed-in tariff (FIT) scenario

The FIT scheme, which has been introduced recently in the UK, has been considered. According to this scheme, µCHP units of capacity less than or equal to 2 kWe will be eligible. The householder will be awarded 11.4 cents per each kWh of generated electricity and a further 3.42 cents per each kWh of exported electricity [14]. Electricity and gas prices are based on typical prices for bulk purchase of fuels at domestic scale, issued by Biomass Energy Centre in January 2010 [23]. The price of natural gas is considered on a fixed rate of €0.04674/kWh based on higher heating value (HHV), and the price of imported electricity is considered at a fixed rate of €0.15162/kWh.

According to the estimate published by the UK's Department for Environment, Food and Rural Affairs (DEFRA), CO_2 emission factors for the UK grid electricity and natural gas equal 0.54418 kg/kWh and 0.18396 kg/kWh, respectively [24]. Maintenance costs are considered to be €0.0171/kWh for both sizes of the µCHP unit and €0.00456/kWh for the back-up heater [4].

A 1 kWe proton exchange membrane fuel cell (PEMFC) has been considered for a semi-detached house (SDH) since it is the optimal size for a PEMFC to be used for this type of demand, according to our sizing model [4]. This demand data, which is the hourly energy consumption of a SDH for a whole year, was collected for low energy dwellings in an area northwest of London. It was accessed through the UK Energy Research Centre's energy data centre [25]. Both electricity and heat demands vary significantly during the day and they also vary significantly from one season to another. Figs. 3 and 4 show these variations for heat and electrical demand, respectively.

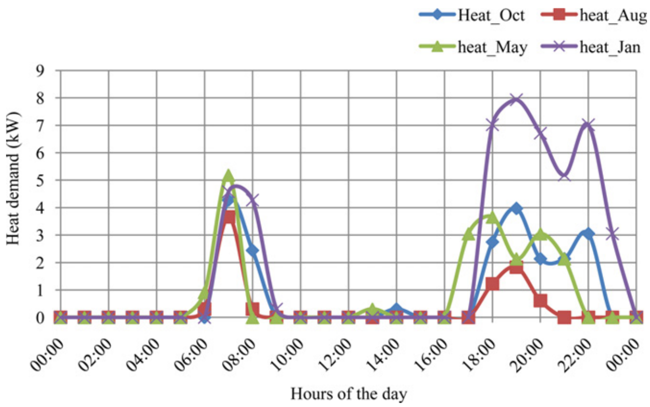

Fig. 3. Heat demand of a representative day from each season.

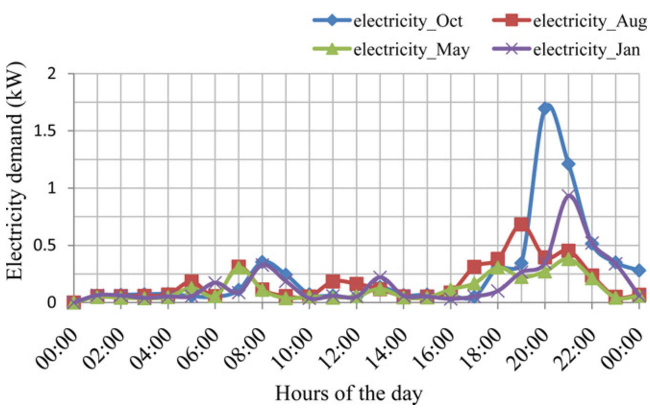

Fig. 4. Electricity demand of a representative day from each season.

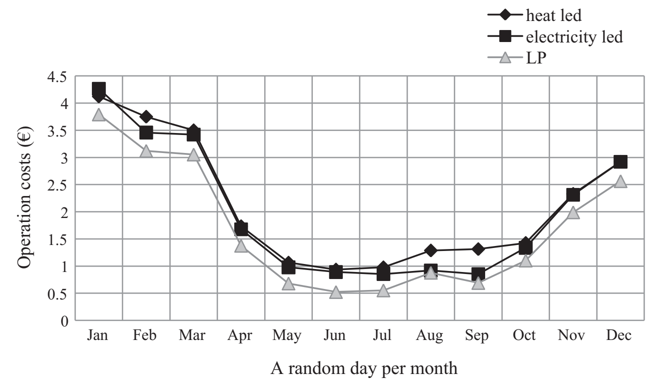

Fig. 6. Operation costs for different strategies when FIT scenario is applied and a 1 kWe PEM is used.

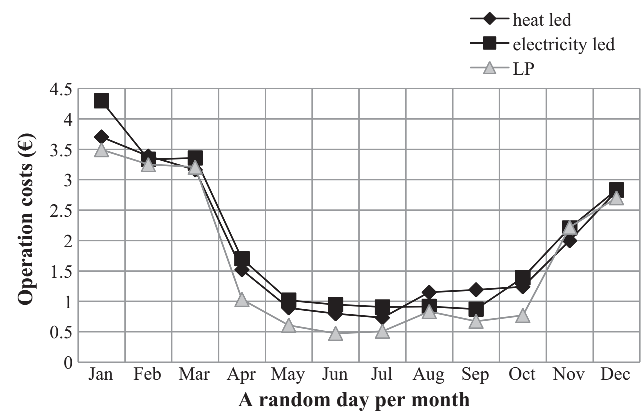

Fig. 7. Operation costs for different strategies when FIT scenario is applied and a 2 kWe PEM is used.

However, a 2 kWe PEMFC has also been considered, to investigate the impact of using the LP optimiser on a larger size. The 2 kWe size was chosen because it is the largest size eligible for the new FIT scheme as mentioned previously. The two conventional predetermined operation strategies, as well as the LP optimiser, have been applied for both sizes of PEMFC. Results are summarised in Fig. 5. The monthly differences between these strategies, in terms of operation costs, are illustrated in Figs. 6 and 7.

When a 1 kWe PEMFC is used, the results show that the developed online LP optimiser has reduced the annual operation costs by approximately €153 and €108 over the heat-led and electricity-led operation strategy, respectively. Similar savings are achieved when a 2 kWe PEMFC is used, where approximately €86 and €123 of annual operation cost have been saved over the heat-led and electricity-led operation strategy, respectively. When considering the 1 kWe PEMFC, an electricity-led strategy results in lower operating costs than a heat-led strategy. However, for a 2 kWe PEMFC, the reverse is true, which is due to the increased revenue gained from exporting electricity. It can also be noted from Figs. 6 and 7 that the LP optimiser reduces the daily operation cost over both heat-led and electricity-led operation strategies in all but one month. However, it can be seen from Figs. 5 and 8 that a 2 kWe PEMFC results in reduced operation costs, in comparison to the 1 kWe PEMFC, when a heat led strategy or the LP optimiser is used. This is because of the increased revenue achieved from exporting electricity. When an electricity led strategy is used, with the 2 kWe PEMFC, almost no reduction in operation costs is achieved.

Typical weekdays and weekend days from January to December have also been investigated. No significant differences have been observed for all strategies. For example, the operation costs, for a

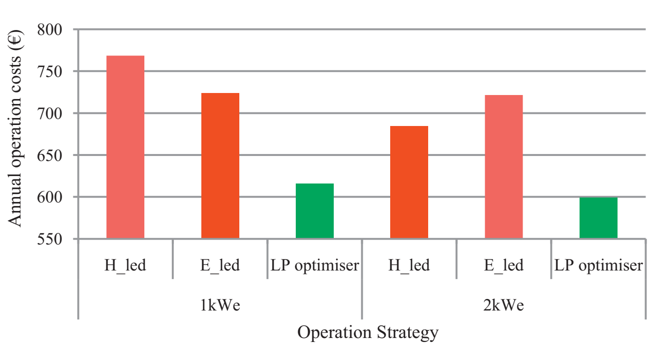

Fig. 5. Operation costs (€) for different strategies when FIT scenario is applied and no carbon tax is considered.

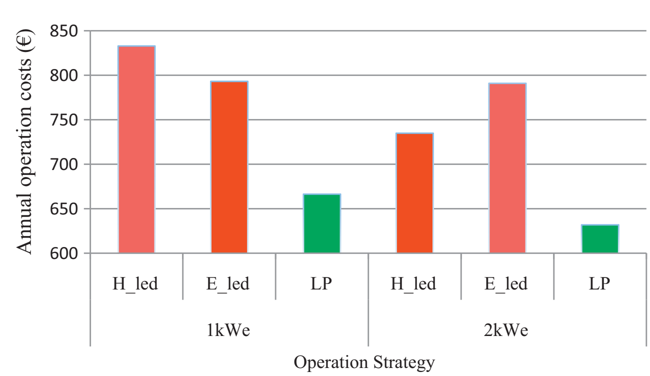

Fig. 8. Operation costs for different strategies when FIT scheme is applied, and a 22.8 €/tonne carbon tax is considered.

Table 2
Annual operation costs and savings (€) for different strategies when electricity trading scenario is applied and 1 kWe PEMFC and 2 kWe PEMFC are used.

Size of PEMFC unit	Operation costs (€)	Exported price 50%			Exported price 75%			Exported price 100%		
		Heat-led	Electricity-led	LP	Heat-led	Electricity-led	LP	Heat-led	Electricity-led	LP
1 kWe	Total	520	471	474	474	471	442	427	471	315
	Savings	0	49	46	0	3	32	44	0	156
2 kWe	Total	544	473	477	442	473	438	339	473	246
	Savings	0	71	67	31	0	35	134	0	227

typical weekend day in January, were less than 6% higher than the operation costs for a typical weekday when using a heat led strategy to operate a 2 kWe PEMFC. Similar results have been observed for the online LP optimiser and the electricity led strategies. In addition, the online LP optimiser achieves lower operation costs, in comparison to the two predetermined conventional strategies for both a typical weekday and a typical weekend day from January to December.

The same FIT scheme simulation scenario was investigated with the addition of a carbon tax of €22.8/tonne since it is expected that this tax may be adopted in the future to encourage the implementation of clean energy technologies. When a 1 kWe PEMFC is used, as shown in Fig. 8, the results show that the online LP optimiser reduces the annual operation costs by approximately €165 and €125 over the heat-led and electricity-led operation strategy, respectively. Similar savings are gained when a 2 kWe PEMFC is used. These results indicate that the developed online LP optimiser reduces annual operation costs over the conventional pre-determined operation strategies.

4.2. Electricity trading scenario

Since the FIT scenario is only applicable to the first 3000 units installed [14], an electricity trading scenario has been considered. In this scenario any surplus electricity generated by μCHP units can be sold and exported to the grid and any deficit in electricity can be purchased and imported from the grid.

The assumed values for maintenance cost and CO_2 emission factors are the same as used in the FIT scenario. However, the price of electricity met by the μG is considered at a fixed rate of €0.09348/kWh; the price of natural gas is considered on a fixed rate of €0.025992/kWh based on HHV [26]. Also, the price of exported electricity is considered at a fixed rate at three different percentage values of retail price: 50%, 75% and 100%.

As in the previous scenario, 1 kWe and 2 kWe PEMFCs have been considered for the same demand profiles. The two conventional pre-determined operation strategies and the online LP optimiser have been applied for each size of PEMFC. Results of using 1 kWe and 2 kWe PEMFCs are summarised in Table 2. The monthly differences between these strategies, in terms of operation costs, when 1 kWe PEMFC is used, are illustrated in Fig. 9.

Results have shown that, when the electricity price of exporting is the same as the retail price (i.e., 100%), using the LP optimiser with a 1 kWe PEMFC reduces the annual operation cost by approximately €156 and €112 over the electricity-led and heat-led operation strategy, respectively. Similarly, when the electricity price of exporting is the same as the retail price, using the LP optimiser with a 2 kWe PEMFC reduces the annual operation cost by approximately €227 and €93 over the electricity-led and heat-led operation strategy, respectively. The monthly differences between strategies in terms of operation costs for a 2 kWe PEMFC are illustrated in Fig. 10.

It can be seen in Table 2 that when the exporting price is less than the retail price (i.e., 50% and 75%), the LP optimiser achieves savings, albeit less significant, when compared with the conventional pre-determined operation strategies.

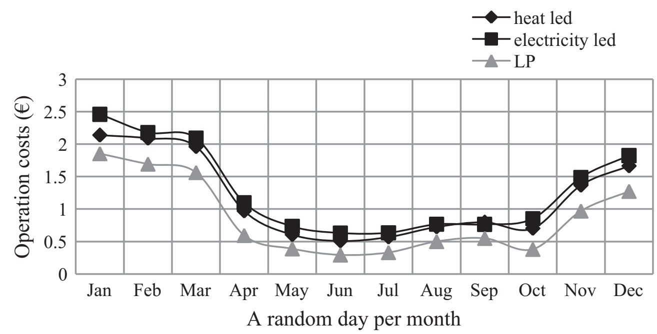

Fig. 9. Operation costs for different strategies when electricity trading scenario is applied, 100% exporting price is considered and a 1 kWe PEMFC is used.

4.3. Carbon tax scenario

For this scenario, the impact of introducing a carbon tax coupled with an electricity trading scenario has been investigated. It is expected that a global CO_2 emission trading system will be a key element in the policies required for ensuring compliance with climate protection targets [27]. The rise in carbon reduction targets over the next decades is expected to lead to corresponding rises in carbon taxes. However, there is uncertainty regarding the extent of these rises ranging from tens of euros per tonne of CO_2 if technologies of carbon capture and storage are successfully developed [28] to several hundreds of euros per tonne of CO_2 under more pessimistic assumptions [29,30]. One of the lowest current estimates in the UK assumes that the implied cost of carbon dioxide is €22.8/tonne of CO_2 [27]. Further, the carbon price support policy has recently been announced by the UK Treasury, which will start at €18.24/tonne CO_2 on the first of April 2013 and it is expected to rise to approximately €80/tonne CO_2 by 2030 [31]. In order to investigate the effects of current and possible future carbon tax values, encapsulating those set out in the UK's current carbon process policy, a range from €0/tonne CO_2 (non carbon tax scenario) to €570/tonne CO_2 were used in the simulations. Within this range, intermediate values of €22.8/tonne, €136.8/tonne, and €228/tonne are also considered.

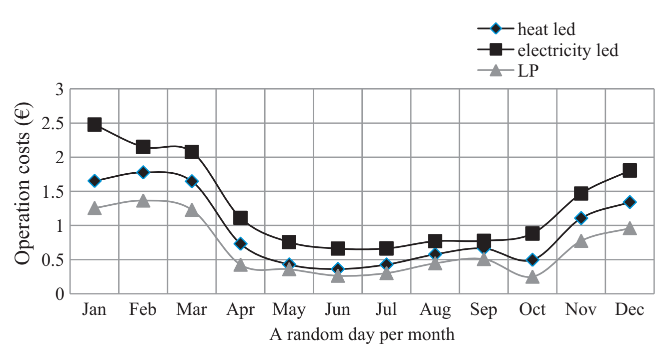

Fig. 10. Operation costs for different strategies when electricity trading scenario is applied, 100% exporting price is considered and a 2 kWe PEMFC is used.

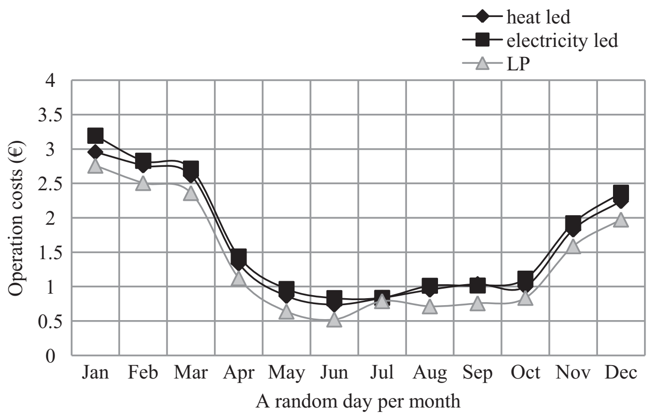

Fig. 11. Operation costs for different strategies when a €22.8/tonne carbon tax is applied, 100% exporting price is considered and a 1 kWe PEMFC is used.

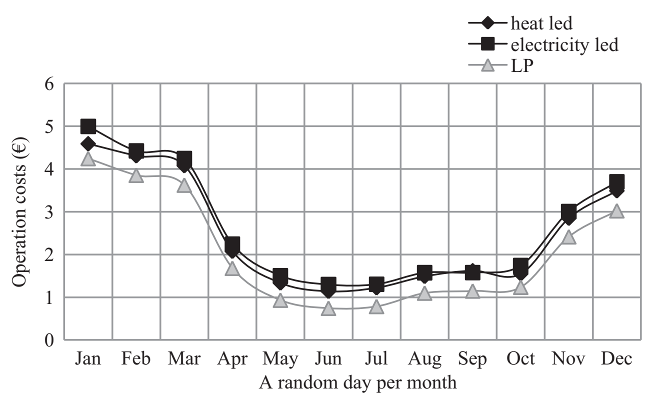

Fig. 12. Operation costs for different strategies when a €136.8/tonne carbon tax is applied, 100% exporting price is considered and a 1 kWe PEMFC is used.

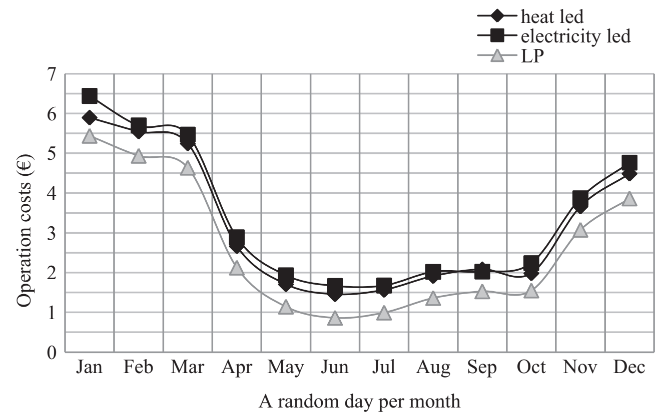

Fig. 13. Operation costs for different strategies when a €228/tonne carbon tax is applied, 100% exporting price is considered and a 1 kWe PEMFC is used.

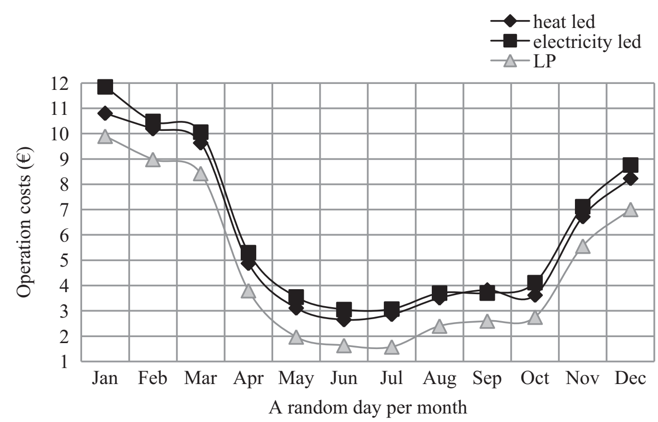

Fig. 14. Operation costs for different strategies when a €570/tonne carbon tax is applied, 100% exporting price is considered and a 1 kWe PEMFC is used.

The same assumptions in Section 4.1 for electricity prices, maintenance costs and CO_2 emission factors have been applied. A 1 kWe PEMFC was considered for the same demand profile used in the previous scenarios. The two conventional pre-determined operation strategies and the LP optimiser have been applied for different values of carbon tax: €22.8/tonne, €136.8/tonne, €228/tonne and €570/tonne in combination with three different values for exporting electricity: 50%, 75% and 100% of retail price. Table 3 shows the resulting annual operation costs when considering carbon tax at the four values stated. The monthly differences between these strategies, in terms of operation costs, when 1 kWe PEMFC is used are illustrated in Figs. 11–14.

From Table 3, it can be seen that increasing the carbon tax significantly increases the savings in operation costs when the price of exporting electricity is the same as retail price. However, introducing a carbon tax when the export price is only 50% of the retail price, leads to significant reductions in the operation costs only when the carbon tax is at its highest level. That is, the LP optimiser can reduce the annual operation costs by €247 against the heat-led strategy and by €299 against the electricity led-strategy when a carbon tax of €570/tonne is used.

Table 3
Annual operation costs (€) for different strategies when different values of carbon tax is applied and 1 kWe PEMFC is used.

Carbon tax (€/tonne of CO_2)	Annual operation costs (€)	Operation strategy								
		Heat-led			Electricity-led			LP optimiser		
		Export price (% of retail price)								
		50%	75%	100%	50%	75%	100%	50%	75%	100%
22.8	Total	671	626	581	614	614	614	622	619	502
	Savings	0	0	33	57	12	0	49	7	112
136.8	Total	995	948	901	958	958	958	965	877	751
	Savings	0	10	57	37	0	0	30	81	207
228	Total	1252	1205	1158	1234	1234	1234	1249	1091	955
	Savings	0	29	76	18	0	0	3	143	279
570	Total	2215	2168	2121	2267	2267	2267	1968	1848	1714
	Savings	52	99	146	0	0	0	299	419	553

5. Conclusions

In the study presented in this paper, the operation of a μCHP unit, combined with a back-up heater and a thermal storage device for typical residential dwellings, has been evaluated. A generic online LP optimiser to determine the optimal operation of a μCHP system has been developed and evaluated. The optimiser has been formulated in a generic form to allow its use for any demand profile and for any μCHP technologies such as ICEs and SEs. This optimiser is capable of minimising the operation costs of such systems. Three different simulation scenarios have been investigated to evaluate the performance of the online optimiser: the feed-in tariff (FIT) scheme, electricity trading and the introduction of a carbon tax.

The results have shown that the optimal online LP optimiser reduces operation costs in comparison with the conventional pre-determined operation strategies in all the scenarios investigated. This optimiser provides a significant reduction in the annual operation costs when a FIT scheme is applied, which can reach approximately €153 when no carbon tax is considered and approximately €165 when a carbon tax is considered. The annual savings, due to using the developed LP optimiser, increase significantly when the price of exporting electricity is the same as the retail price, which for example was approximately €227 when 1 kWe PEMFC was used. Introducing a carbon tax maximises the benefits from using the developed online LP optimiser, where the annual savings can reach €553 when a carbon tax of €570 per tonne of CO_2 is considered. It is emphasised that the LP optimiser achieves the greatest savings when the export price is the same as retail price and the carbon tax is at the highest level.

In summary, it is suggested that the online optimiser has the potential to deliver significant energy savings and operation cost savings in practice. That is, it is suggested that the continuously operating LP optimiser could be embedded within the control systems of μCHP technologies. Indeed, the adoption of the optimiser presented in this paper has the potential to make a significant contribution to the widespread proliferation of μCHP technologies.

Appendix A. Nomenclature

Type of variables	Symbol	Description	Units
Operation variables	$o_{el,i}$	Electrical output of μCHP unit during the *i*th hour	kWh
	$o_{th,i}$	Thermal output of backup-boiler during the *i*th hour	kWh
	$o_{im,i}$	Imported electricity from the μG during the *i*th hour	kWh
	$o_{ex,i}$	Exported electricity to the grid during the *i*th hour	kWh
	$o_{st\_in,i}$	Thermal input to the storage device during the *i*th hour	kWh
	$o_{st\_out,i}$	Thermal output from the storage device during the *i*th hour	kWh
Costs	c_{DO}	Daily operation cost	€
	α	Cost of a kWh electricity produced by μCHP unit	€/kWe
	β	Cost of a kWh heat produced by back-up heater	€/kW_{th}
	γ	Cost of an imported kWh of electricity	€/kWh
	δ	Cost of an exported kWh of electricity	€/kWh
	ε	Total cost of a kWh of heat entering the storage device	€/kWh
	ξ	Total cost of a kWh of heat used from the storage device	€/kWh
	C_{NG}	Cost of a kWh of natural gas	€/kWh
	C_{imp}	Price of importing kWh of electricity from the grid	€/kWh
	C_{exp}	Price of exporting kWh of electricity to the grid	€/kWh
	$m_{\mu CHP}$	Maintenance cost per kWh of μCHP electrical output	€/kWh
	m_B	Maintenance cost per kWh of back-up thermal output	€/kWh
	FIT_G	Feed-in tariff for generated electricity	€/kWh
	FIT_{ex}	Feed-in tariff for exported electricity	€/kWh
Technical inputs	R_{CHP}	Size (rating) of μCHP unit	kWe
	R_B	Size (rating) of backup-boiler	kWth
	R_s	Size (rating) of thermal storage device	kWh
	η_e	Electrical efficiency of μCHP unit	
	η_{th}	Thermal efficiency of μCHP unit	
	η_B	Efficiency of back-up heater	
	η_s	Round trip efficiency of the thermal storage device	
	Q	Heat to power ratio of μCHP unit	
	R_d	Maximum ramping down rate of μCHP unit	kWe/h
	R_u	Maximum ramping up rate of μCHP unit	kWe/h
Others	n_h	Number of hours in a day	
	e_{NG}	CO_2 emission factor of kWh of natural gas	kg/kWh
	e_{Grid}	CO_2 emission factor of electricity from the grid	kg/kWh
	t_C	Carbon tax per tonne of CO_2 emissions	€/tonne
	L_j	Forecasted electricity demand in time period *j*	kWh
	H_j	Forecasted heat demand in time period *j*	kWh
	LHV	Lower heating value of natural gas	kWh/kg
	HHV	Higher heating value of natural gas	kWh/kg

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