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Modelling and optimisation in terms of CO₂ emissions of a solid oxide fuel cell based micro-CHP system in a four bedroom house in London

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Abstract

One of the most promising technologies for reducing energy consumption is combined heat and power (CHP). CHPs benefit from the simultaneous generation of electricity and heat increasing their total utilisation of fuel, thus their efficiency. Current research on fuel cell CHPs is focused on detailed fuel cell models that use basic information of the building energy requirements. A deeper understanding of the process of integration of the fuel cell CHP on to the building energy system is required. Fuel cell based micro-CHP system components need to be sized appropriately to satisfy the domestic energy demand profile and to serve heat loads effectively. It is also important to define the operation strategy (scheduling of demands, electricity/heat generation etc.) and the control method that is utilised to meet the building energy demands because they define the overall performance and efficiency of the building energy system as a whole.

In this paper an investigation of the design of a SOFC based micro-CHP under varying conditions is carried out and ways of integration with the building energy system are presented. A mathematical model that describes the operation and control of a fuel cell micro-CHP based system in residential dwellings has been developed and is demonstrated. The model is dynamic and includes the fuel cell, the backup gas boiler, and hot water thermal storage. The evaluation is based on a new UK residential dwelling in accordance with the current building regulations and includes electricity, heating and domestic hot water loads. The aims are to investigate methods of integration of the fuel cell based micro-CHP with the fluctuating energy patterns and examine the benefits of electricity and heating generation using fuel cell CHPs in residential buildings.

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1. Introduction

The amount of energy that is consumed by all buildings, commercial and domestic, is responsible for about 45% of total energy consumption in the UK [1]. Energy efficient technologies such as Combined

Heat and Power have been implemented that can reduce CO₂ emissions and fulfil the energy demand in buildings. Combined Heat and Power, aka cogeneration is the use of one process to simultaneously generate both electricity and useful heat. There are various technologies that can be used as the driving force of a CHP system and their suitability depends on the scale of the application, the energy characteristics and the economics.

Nomenclature		E_t	Electricity Consumption per time step (kW)
<i>Abbreviations and indices</i>		g_g	Gas Emission Factor (kgCO ₂ / kWh)
CHP	Combined Heat and Power	G_t	Total Gas Consumption per time step (kW)
DC	Direct Current	$G_{t,fc}$	Fuel Cell Gas Consumption per time step (kW)
DHW	Domestic Hot Water	$G_{t,aux}$	Auxiliary Boiler Gas Consumption per time step (kW)
HT	High Temperature	j	Plant type: fuel cell or auxiliary boiler
FIT	Feed in Tariff	t	Time Step (h)
MILP	Mixed Integer Lineal Programming	$Q_{req,t,ele}$	House Demand per energy type (kW)
NCM	National Calculation Method	$Q_{t,j,ene}$	Energy output of j per time step (kW)
PEMFC	Proton Exchange Membrane Fuel Cell	$h_{t,j}$	Efficiency of Plant j
RHI	Renewable Heat Incentive	z	Objective Function (kgCO ₂)
SOFC	Solid Oxide Fuel Cell		
<i>Parameters and Variables</i>			
g_e	Grid Electricity Emission Factor (kgCO ₂ / kWh)		

Energy demand in domestic dwellings is largely provided by conventional means, grid electricity and gas fired boilers. New buildings are required by building regulations to be constructed using materials that reduce heat loss and equipment that is more efficient than before to reduce their environmental impact [2]. Micro-CHP systems powered by fuel cells could be used to serve domestic loads efficiently, meet heating and some electricity needs of residential dwellings. This technology can achieve higher electrical efficiencies than heat engines. However, the operation of the fuel cell is constrained by a low heat-to-power ratio which makes it not suitable to all domestic applications.

The design of fuel cell based micro-CHP systems is a complex task, as all components need to be sized appropriately to satisfy the domestic energy demand profile and to serve heat loads effectively. Residential electricity, heating and hot water demands fluctuate daily and seasonally. Similarly, the operation of the fuel cell is subject to constraints. It is therefore important to define the operation strategy (scheduling of demands, electricity/heat generation etc.) and the control method that is utilised to meet the building energy demands because they define the overall performance and efficiency of the building energy system as a whole. Typically, fuel cells would displace more energy and perform better when they operate constantly and at the highest output. Fuel cells are not flexible enough to match the highly variable and unpredictable energy demands of a house. Therefore, in many cases an auxiliary boiler and a thermal storage tank are required in the design to flatten out the heating load peaks. Sizing the thermal tank however is a difficult task as space, cost and heat availability influence the decision. For most domestic applications, the tank volume varies between 100 and 500 lit.

2. Background

2.1. Modelling Fuel Cell micro-CHPs for domestic applications

Modelling goals include the estimation of the environmental benefits in terms of CO₂ emissions reductions and primary energy savings, or the reduction in operating costs from reduced purchase of electricity. Some researchers follow simulation methods and analyse different scenarios. However, other researchers choose optimisation methods in order to calculate values for their chosen design variables that maximise or minimise an objective function. Techno-economic studies usually apply multi-objective optimisation methods and identify trade-offs between cost and a technical characteristic such as electrical efficiency or delivered power. A techno-economic study was performed by Hawkes et al [3, 4] that calculated the maximum additional capital cost an investor would pay for the fuel cell micro-CHP system over and above what they would pay for a competing conventional heating system and the impact of stack degradation on economic and environmental performance. The level of sophistication in the developed models amongst researchers differs according to their background and their anticipated outcomes. In terms of the models for domestic applications of fuel cell micro-CHP in literature there seem to be two general themes regardless of the choice of approach (optimisation or simulation):

1. Fuel cell models which represent the fuel cell micro-CHP components and operation in detail and may include cost (techno-economic modelling) or other characteristics but do not take into account the presence of the building and its energy consuming characteristics [5-8].

2. Fuel cell micro-CHP models which take into account not only the fuel cell itself but also the interaction with the building and its energy profiles. These models vary from author to author in terms of their definition of the “typical house”. They often include data sets from domestic energy surveys or they take their energy load profiles by using Building Simulation Software. They represent a more accurate description of the system and they don't only focus on the fuel cell side. Authors that have followed this approach are included in [8, 9].

Particular attention has been given recently in modelling thermal storage when used with micro-CHP systems. The common point is that they try to find the optimum size of the storage tank among different constraints [10, 11].

The main conclusions arising from researching existing literature in modelling fuel cell micro-CHPs are the following:

- Fuel cell micro-CHPs operate better in houses with lower heating than electricity demands because of their low heat-to-power ratio. Also it is better suited to houses with a large energy demand, as the system can operate longer hours without its output being constrained by lack of demand
- Fuel Cell micro-CHPs require policy schemes and government involvement in order to present an attractive investment for homeowners [12].
- The addition of thermal storage increases the benefits of fuel cell micro-CHP systems [9]
- Researchers tend to have their own interpretation of the “typical dwelling energy requirements” which leads to different modelling results.

3. Building Simulation

A model, which combines building simulation and mathematical modelling, was developed. We defined a reference four bedroom house and modelled it in the building simulation software IES. The purpose is dual: Firstly, to generate heat loss and electricity demand data for the building (independent of the heating system choice). These data represent the input required by a heating and electricity system and can be used as input for the mathematical model developed further on. Secondly, to model and calculate the heat output of a conventional boiler to satisfy the heat requirements calculated in the first step. This would enable us to define a reference building that will provide the basis of comparison between a conventionally designed heating system and the fuel cell micro-CHP system designed through optimisation using our mathematical model.

The selected building is located in London, it covers a floor area of 190 m² and is compliant with Building Regulations L2B 2010 in terms of U values and air permeability [2] (see Table 1). Heating is served by a natural gas fired condensing boiler. The efficiency of the boiler is compliant with the domestic heating compliance guide and was set at 90% [13]. Electricity is provided from the grid. The performance of the building was evaluated using typical heat and electricity profiles. In order to be able to model a dwelling's operation in any building modelling software apart from the structural thermal characteristics and the building services system, a good approximation of how the system is operated is required. Therefore daily, monthly and yearly profiles of operation are used in order to describe the operation of lights, hot water requirement etc. A 24 hour example is illustrated of a profile is shown in Figure 1. These profiles are included in the National Calculation Method (NCM) [14].

Table 1. U Values and Air Permeability used in the evaluation

	Value
Roof	0.2 W/m ² K
Wall	0.3 W/m ² K
Floor	0.25 W/m ² K
Windows, Rooflights	2.0 W/m ² K
Doors	2.0 W/m ² K
Air Permeability	10 m ³ hr/m ²

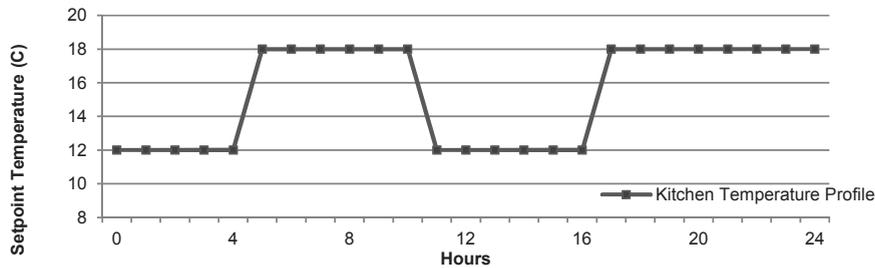
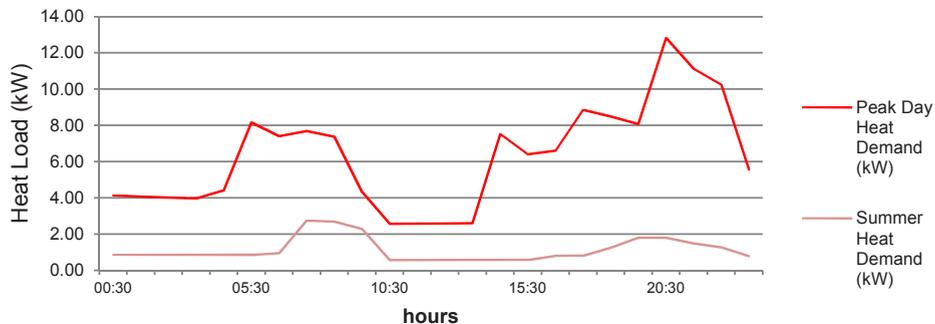
**Figure 1 Daily Profile of Kitchen Set Point Temperature**

Figure 2 shows the calculated heat requirement for the peak winter day and a typical mid-summer day. The patterns follow the house activities. In winter, there is high heat demand in the morning when occupants typically wake up and enable the heating system and consume DHW. It also peaks in the night when the outside temperatures drops and heating is activated. The summer heat requirement is only caused by DHW and it peaks in morning and evening hours, at periods of high DHW demand. The approximately 1 kW base load is used to maintain the temperature of the DHW tank above 50-55 C (to protect from the development of legionella bacteria).

Now that heat and electricity demand data (in hourly time steps) have been produced for the reference building, they will be used as input parameters for the mathematical model that will be described below.

**Figure 2 Peak Day Winter and Summer Heat Demand**

4. Micro-CHP fuel cell model

The basic principles are that heating and electricity demands, calculated in IES, need to be satisfied at all times and that heating is served by the fuel cell and the auxiliary boiler. Electricity is served by the fuel cell and grid electricity. The objective is to minimise the total CO₂ emissions (z) resulting from the operation of the house:

$$z = g_g \sum_1^t G_t + g_e \sum_1^t E_t$$

G_t is given by the following equation

$$G_t = G_{t,fc} + G_{t,aux} = \frac{Q_{t,fc,ele}}{h_{fc,ele}} + \frac{Q_{t,aux,htg}}{h_{aux}}$$

The two following equations represent the electrical and the thermal energy balance respectively. The balance is performed between the source (plant) and consumption of energy (house).

$$E_t + Q_{t,fc,ele} = Qreq_{t,ele}$$

$$Q_{t,fc,htg} + Q_{t,aux,htg} = Qreq_{t,htg}$$

The SOFC micro-CHP and auxiliary boiler are treated as black boxes that convert the energy input to electricity and heat according to their efficiencies. The fuel cell micro-CHP thermal and electrical efficiencies were taken from [9]. The electrical efficiency is a net DC system efficiency defined as the ratio between the net DC electrical power produced by the system and the chemical energy in the inlet fuel feed. The thermal efficiency is the fraction of the chemical energy in the inlet fuel feed that is recovered as heat and the overall efficiency is the sum of these two efficiencies.

$$h_{t,fc,htg} = -23.548r^6 + 131.17r^5 - 295.99r^4 + 355.63r^3 - 251.5r^2 + 121.96r$$

$$h_{t,fc,eele} = -1065r^6 + 4114.7r^5 - 6437.1r^4 + 5224.5r^3 - 2330.7r^2 + 536.81r$$

Binary variables were used to indicate which plant is operational in each time step. The fuel cell's operation is constrained by a minimum turn down ratio which is set to 20% and a ramp up rate of 15 W_e/h ($= 0.9$ kW/h) [15].

Table 2. Model set and parameters

Sets	Description	Value
t	Time step	[1 hour steps]
j	Plant type	[fc,aux]
k	Energy type	[htg,ele]
Parameters	Description	Value
Qreq	House energy requirement	varies
h_{aux}	Auxiliary boiler thermal efficiency	0.9
ramp	Fuel cell ramp up rate	0.9 kW _e /h
g_g	Natural gas emission factor	0.194 kgCO ₂ /kWh
g_e	Grid electricity emission factor	0.517 kgCO ₂ /kWh

Similarly the boiler's operation is constrained by a minimum turn down ratio of 30% which is a typical industry standard [16].

The model includes a thermal storage tank, characterised by the volume, the energy content, constrained by maximum energy content, and the energy flow from the plant to the tank and from the tank to the house. Schematics of the two configurations under examination can be seen in Figures 3 and 4.

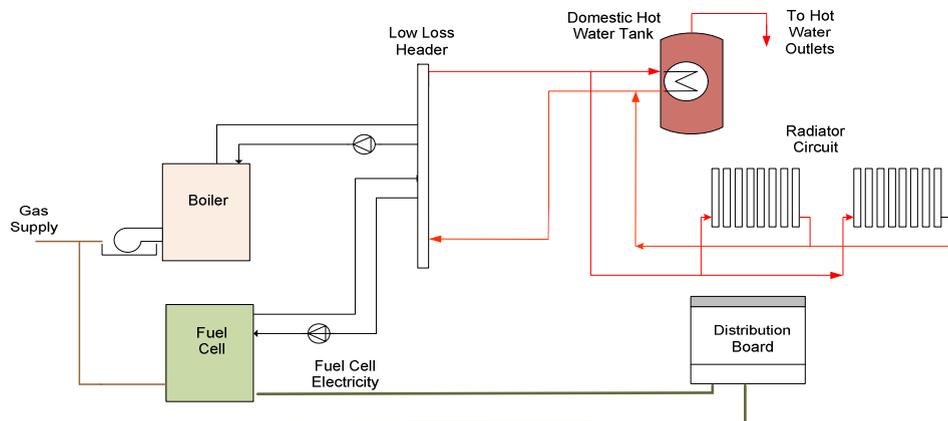


Figure 3 Fuel Cell micro-CHP without thermal storage used in the analysis (systems 1, 2, 3)

4.1. Implementation

As binary variables were used and the efficiency equations are non-linear, the model was formulated as a mixed integer nonlinear programme and implemented in GAMS[12]. GAMS is a commercial software for mathematical programming and optimisation. GAMS is a tool that can handle complex, large scale modelling applications, and allows the user to build large maintainable models. GAMS provides the user a variety of optimisation tools, one of which is SBB; SBB was used to solve the model. SBB may perform better than other solvers on models that have fewer discrete variables but more difficult nonlinearities which is the case of the implemented model [17]. The SBB solver is based on a combination of the standard Branch and Bound method and other solvers to solve the relaxed NLP problem.

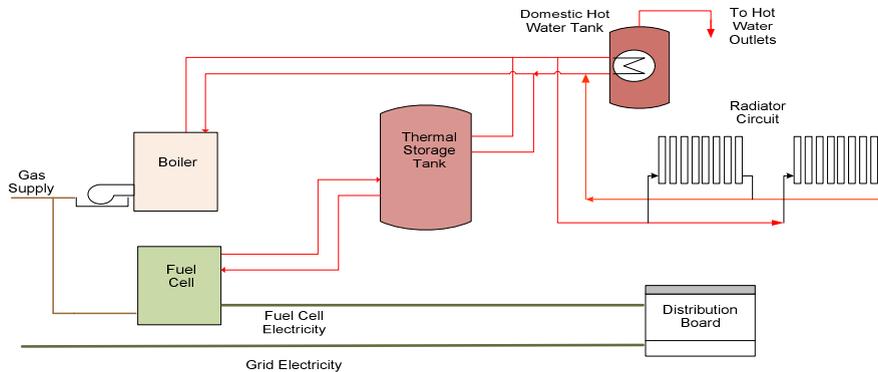


Figure 4 Fuel Cell micro-CHP with thermal storage used in the analysis (systems 4, 5, 6)

The model was applied to two configurations, without and with storage tank, for the following date sets:

1. Winter peak day (24 hours): Systems 1 and 4.
2. Summer day (24 hours): Systems 2 and 5.
3. A combined winter-summer data set for two days (48 hours): Systems 3 and 6.

Systems 1, 2 and 3 represent a configuration without the use of thermal storage and systems 4, 5 and 6 include storage (see figures 3, 4). Overall 6 systems were evaluated.

Choosing these three different time periods would enable us to observe the optimisation results for different time periods and their variation with the weather conditions and associated energy demands. The winter peak day analysis could represent a dwelling with high heat-to electricity requirement and the summer day analysis a dwelling with low heat-to-electricity requirement, identifying how the fuel cell system operates in essentially different types of dwellings. The 48-hour analysis will give a design proposal that trades off better the different requirements of the whole year. It will also provide a general guideline on how the plant should operate.

5. Analysis and Results

5.1. Optimisation Results and Discussion

Table 3 lists the findings of the study. The fuel cell maximum electrical capacity ranges from 1.9-2.5 kW in all cases which is similar to the existing available products. The inclusion of storage increases the system's energy availability and smoothens the peak loads especially in winter. It reduced the maximum capacity of the auxiliary boiler in the winter day from 11 kW to 8.5 kW and generally reduced its hours of operation. The storage enabled the fuel cell to satisfy the electricity requirement and minimise electricity grid import even when heat demand was low by producing the required electricity and storing the generated heat in the storage tank. The effect of storage is greater in winter rather than in summer. The results obtained for storage systems however are based on the assumption that there is no heat loss to the surroundings. For the summer, the capacity of the auxiliary boiler drops to 1 kW and 2.3 kW for the two configurations respectively. This value is not realistic as there are no available gas boiler products rated at 1 or 2.3 kW, but gives an indication of how small the output of the boiler needs to be in a summer day. The 48 hour analysis, which includes both winter and summer data, showed that emissions are only reduced by including thermal storage. The effect of the operation of the boiler is evident when comparing the emissions of System 3 and 6. System 3

does not offer any significant reduction from the reference building. This is primarily an effect of the sizing of the boiler (which capacity is required to cover the winter loads) and its minimum turn down ratio which is 30%. Each time there is heat requirement that cannot be covered by the fuel cell's thermal output, the boiler will operate but sometimes its minimum output exceeds the output needed. This causes the additional CO₂ emissions. This result is not indicative of the overall effect of the fuel cell micro-CHP system throughout the year but suggests that this configuration is not ideal in terms of reducing primary energy consumption.

Table 3 Summary of optimisation results

	Data Set	CO ₂ emissions (kgCO ₂)	Reference Building (kgCO ₂)	Reduction from reference system	Optimum Auxiliary Boiler Capacity (kW)	Optimum SOFC Fuel Cell micro-CHP Electrical Capacity (kW)	Storage Tank Volume (m ³)
System 1	Winter	41.8	45.06	7.81%	11.1	1.9	-
System 2	Summer	12.9	16.46	20.53%	1	2	-
System 3	48 hours	61.2	61.52	0.05%	11	2	-
System 4	Winter	40.9	45.06	10.11%	8.5	1.9	0.49
System 5	Summer	13.1	16.46	17.80%	2.3	2.2	0.29
System 6	48 hours	54.6	61.52	11.3%	10.3	2.5	0.76

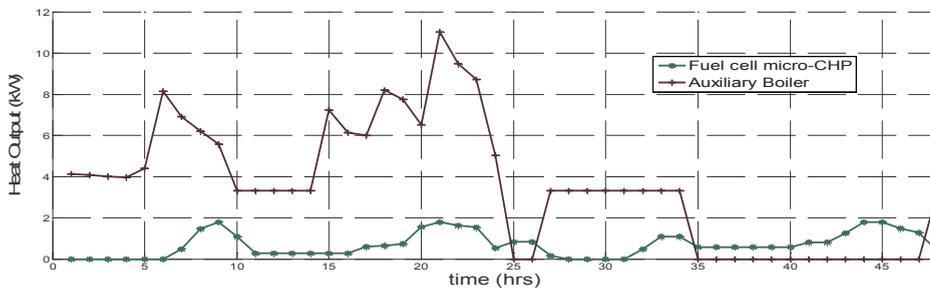


Figure 5 Graph representing the heat output of the fuel cell micro-CHP and auxiliary boiler for System 3 (without storage)

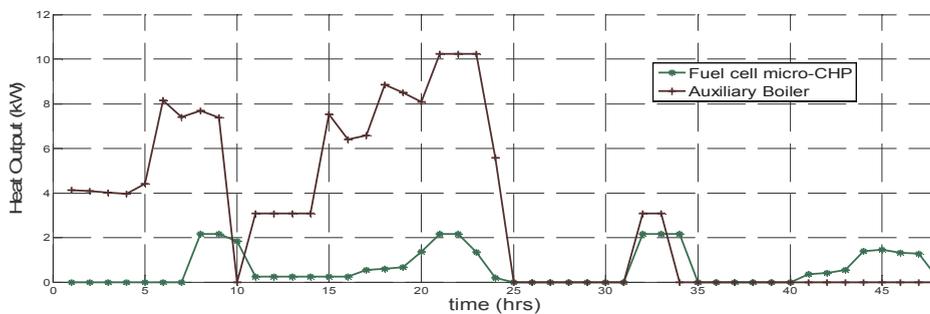


Figure 6 Graph representing the heat output of the fuel cell micro-CHP and auxiliary boiler for System 6 (with storage)

On the other hand, when energy storage is used the reduction reaches 11.3%; the boiler operation is minimised between hours 25 and 48 and heat is covered almost entirely by the storage tank. This can be observed in Figures 6 and 7. Fuel cell micro-CHPs because of their low heat-to-power ratio operate better in houses with lower heating than electricity demands. This can be confirmed by this study because of the higher reductions achieved for the summer scenarios where heat and electricity demand are of the same order. Figure 8 shows the total CO₂ emissions of each system broken down to the emissions caused by the boiler, the fuel cell and the electricity grid. The effect of the operation of the boiler is noticeable when comparing the emissions of System 3 and 6.

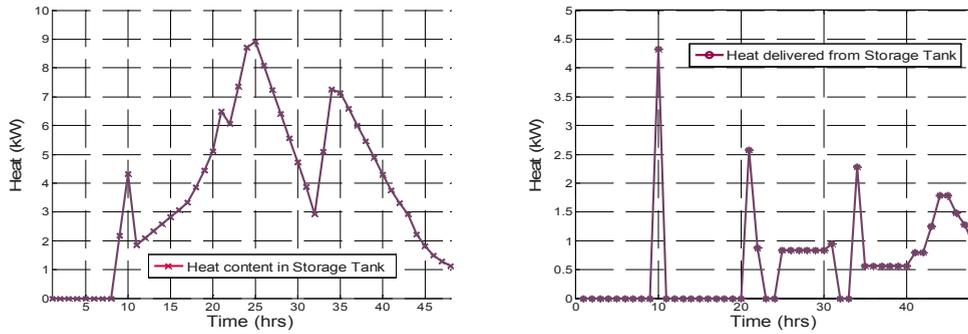


Figure 7 Graph representing the heat content and the output of the thermal storage tank for System 6 (with storage)

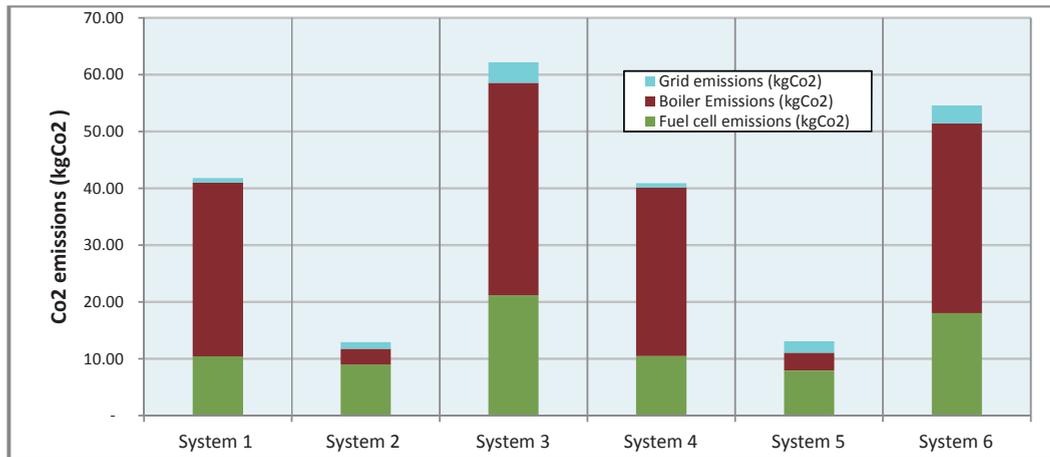


Figure 8 Graph representing the optimised total emissions of each configuration examined

6. Conclusions

This study has presented a micro combined heat and power system model for use in an environmental benefit analysis considering some options for provision of residential energy demand in the UK. Data sets for different weather scenarios were developed based on different configurations with the aim of determining sizing characteristics and operation profiles of all plant involved in the system. Thermal energy storage was also considered as one of the heating options in addition to the boiler and the fuel cell. The study showed that a fuel cell micro-CHP system with thermal storage, evaluated on a data set that includes winter and summer data can provide CO_2 savings in the order 11.3 % from a conventionally designed building. It was also found that micro-CHP systems are more suitable in houses whose electricity load is on the same order of the heat demand. Thermal energy storage coupled with the fuel cell micro-CHP was the system that performed better on a data set based on winter and summer house heating and electricity loads. It allowed the fuel cell to store heat in the storage tank in periods of low heat demand to be used later when demand was higher without having to rely on the auxiliary boiler. The importance of this study is that it considers the plant and house as one and optimises the whole system. It has identified some key points in the design and operation of fuel cell micro-CHP and their interaction with the house system.

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