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Solid oxide fuel cell micro combined heat and power system operating strategy: Options for provision of residential space and water heating

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Abstract

Solid oxide fuel cell (SOFC) based micro combined heat and power (micro-CHP) systems exhibit fundamentally different characteristics from other common micro-CHP technologies. Of particular relevance to this article is that they have a low heat-to-power ratio and may benefit from avoidance of thermal cycling. Existing patterns of residential heat demand in the UK, often characterised by morning and evening heating periods, do not necessarily complement the characteristics of SOFC based micro-CHP in an economic and technical sense because of difficulties in responding to large rapid heat demands (low heat-to-power ratio) and preference for continuous operation (avoidance of thermal cycling). In order to investigate modes of heat delivery that complement SOFC based micro-CHP a number of different heat demand profiles for a typical UK residential dwelling are considered along with a detailed model of SOFC based micro-CHP technical characteristics. Economic and environmental outcomes are modelled for each heat demand profile. A thermal energy store is then added to the analysis and comment is made on changes in economic and environmental parameters, and on the constraints of this option. We find that SOFC-based micro-CHP is best suited to slow space heating demands, where the heating system is on constantly during virtually all of the winter period. Thermal energy storage is less useful where heat demands are slow, but is better suited to cases where decoupling of heat demand and heat supply can result in efficiencies.

Keywords: Solid oxide fuel cell; Thermal energy storage; Heat; Residential; Micro-CHP

1. Introduction

The efficiency of energy supply and demand in the residential sector is the focus of much attention in the UK. It is perceived that substantial progress can be made towards meeting national greenhouse gas emission reduction targets through measures in this sector. On the supply side, efficiency gains can be made by improving the efficiency of centralised power stations, optimising transmission and distribution infrastructure, or installing more efficient combined heat and power or highly efficient boiler technology at or near the point of demand. Within this broad area, this article focuses on modes of residential heat delivery that complement solid oxide fuel cell (SOFC) micro combined heat and power (micro-CHP) in an economic sense, and also considers the environmental implications of those outcomes.

Gas was the primary heating fuel used in heating in the UK, accounting for approximately 80% of demand in 2001 [1]. Boiler-based gas heating systems are generally categorised as combination, regular, or system arrangements. Combination arrangements provide instant heating of cold water and are relatively compact and efficient. Regular arrangements are vented and include a cistern assembly to provide overflow and rapid refill (normally situated in the roof cavity) plus a thermal energy storage cylinder, whilst system arrangements are typically unvented and pressurised and include only the thermal energy storage cylinder. However, the systems burning this gas

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were not particularly efficient with less than 2% of gas centrally heated homes benefiting from a condensing model boiler [1]. Clearly residential heat supply in the UK could be more efficient, and new regulations which require all new boiler installations to be condensing models have been enacted [2] in an attempt to address this issue.

Another method to improve the efficiency of residential energy supply is through installation of micro-CHP. Solid oxide fuel cell (SOFC) based micro-CHP generates electricity and heat simultaneously, and can therefore supply residential energy with relatively small energy losses. This avoids the “double” greenhouse gas emissions created when electricity is produced at a centralised power station and waste heat is discarded and then heat is produced again in the household by burning gas, oil, solid fuels, or a combination of direct and storage electric heating. For a typical UK dwelling with a 1 kW_e SOFC-based micro-CHP system one would expect a carbon dioxide emissions reduction of the order of 800 kg $dwelling^{-1}$ $year^{-1}$ [3] over the case where electricity is supplied via a grid-average mix of generators and heat is supplied via burning gas in a condensing boiler.

SOFCs are an emerging technology with significantly different characteristics to conventional generators [4]. Amongst other features, SOFC have generally high electrical efficiency (and therefore low heat-to-power ratio), and high part-load efficiency. They operate at elevated temperatures of around 500–1000 °C and therefore produce high-grade heat that could be utilised within a house. However, as they are under development, there are a number of constraints yet to be resolved. One of these is the avoidance of voltage degradation over the lifetime of the stack, which may be accelerated by thermal cycling. Although research in this area suggests there may be solutions to this issue, it is informative to investigate what influence it has on the investment attractiveness of SOFC-based micro-CHP, and the possibility for economic solutions that circumvent this problem. This paper explores various modes of heat delivery and the possibility of thermal energy storage to complement SOFC-based micro-CHP in an economic and technical sense. Economic benefits of changing the heat demand profile may arise from more of the house electricity and heat demand being co-incident and within the power capacity of a reasonably sized SOFC stack, and technical benefits may be achieved through avoidance of thermal cycling of the stack.

2. Background

A literature review of the topic addressed by this article revealed a number of interesting studies. Kato et al. [5] completed a study of system and thermal energy storage (TES) capacities for a residential PEMFC co-generation in an apartment block. They noted that a fine temporal precision was required to adequately capture the dynamics of domestic hot water (DHW) demand and to correctly size the system components. Results of their study were that TES capacity of 200–350 l was required when coupled with a 2 kW_e PEMFC system, but this capacity reduced ($dwelling^{-1}$) when several properties in the apartment block were aggregated. The study assumed 100% efficiency of hot water storage. Reviewed articles with similar aims included Baughman et al. [6] and Kostowski and Skorek [7] who considered the thermodynamic, engineering and economic optimum capacity of TES for commercial applications. Baughman et al. found that addition of a cold TES to an industrial plant had a substantial positive net present value (NPV), and the addition of absorption chillers and co-generation resulted in a significant additional improvement in NPV. Kostowski and Skorek developed a more detailed model of hot TES, incorporating heat transfer concepts and stratification, and proceeded to optimise TES volume based on maximisation of change in NPV due to the TES. They found that TES was economic and served to decrease total energy consumption in the facility.

There are many examples of modelling and economics based work surrounding TES systems in general. For example, Rosen et al. [8] consider the effect of stratification (defined as the division of water into layers of different temperature inside the TES) on energy and exergy capacities in thermal storage systems and found that use of stratification in TES design increases the exergy storage capacity of the TES and exergy analysis should be applied in the analysis and comparison of stratified TES. Bedouani et al. [9,10] modelled and experimentally validated a central electric thermal storage system for residential use, and performed a techno-economic study of the system. Amongst other results, they found that the system was only economically viable if some time-of-use tariff is in effect. Overall there is a significant body of knowledge spanning several decades regarding TES, which is clearly a well understood and frequently applied technology.

One final study of specific interest to the present article is Voorspools and D’haeseleer [11]. Their thesis indirectly concerns the heat-led nature of most micro-CHP, and makes the observation that because most micro-CHP is heat-led[1] it operates less consistently in summer months when there is little or no heat demand. Therefore, micro-CHP may indirectly create an increase in greenhouse gas (GHG) emissions because if many units are installed they might displace the construction of new high efficiency centralised generation (e.g. CCGT) and as a result causes older less efficient generation to operate in summer. Voorspools and D’haeseleer noted that more constant operation (i.e. in summer as well) of the micro-CHP could reverse this result. The authors of the present article note that SOFC-based (or any high-efficiency) micro-CHP may provide a solution to this issue in that; (a) it has a low heat-to-power ratio and may therefore be able to operate in summer, and (b) when coupled with thermal storage the options for economic use of the system heat output multiply.

In addition to the literature surrounding the specific topic analysed in this article substantial work is being carried out in the general area of efficiency of residential energy supply and development of a number of types of micro-CHP. Development of micro-CHP systems is currently underway at a number of companies such as BG MicroGen, EcoPower, WhisperGen,

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[1] “Heat-led” means that the system is turned on when there is a heat load present, and turned off or modulated when there is no heat load or reduced heat load.

Ceres Power, Ceramic Fuel Cells Limited, Sulzer Hexis and Baxi to name a few. At least 25 companies are developing fuel cell micro-CHP worldwide [12].

3. Aims and method

The aims of this article are to investigate and discuss the potential for different heat delivery modes to improve the overall economics of SOFC-based micro-CHP systems, and to investigate and discuss the potential for thermal energy storage to improve the overall economics of SOFC-based micro-CHP systems. Although the economics of each option are the focus of the work, the environmental outcomes in terms of carbon dioxide emissions are also considered in each case. The thesis is that SOFC-based micro-CHP is better suited to "slower" heating demands where heat up and cool down occurs over several hours rather than tens of minutes, and that there are environmental benefits in using this approach. Secondary aims of this article are to demonstrate application of a model of an anode-supported direct internal reforming SOFC-based micro-CHP system developed by some of the authors, and to contribute to and apply models of residential thermal demand for an average UK dwelling.

Firstly, we present a SOFC-based micro-CHP system model developed by some of the authors and discuss the development and theory behind this model. Secondly, we present the residential thermal demand profiles for a typical UK dwelling, and discuss the associated assumptions. Thirdly, we present improvements to an existing energy provision cost-minimisation model (CODEGen) that chooses the least-cost SOFC-based micro-CHP system to install in a property and the optimum dispatch strategy for that system. This optimisation algorithm is updated to consider thermal energy storage (TES) as an option. Finally we apply the improved cost-minimisation model to consider the economics and environmental outcomes for SOFC-based micro-CHP systems for the developed thermal demand profiles with and without thermal storage present in the system.

4. SOFC-based micro-CHP system model

For operation, a solid oxide fuel cell (SOFC) must be embedded within a SOFC system incorporating a balance of plant (BoP) that supplies air and clean fuel, converts the direct current (DC) to alternating current (AC), and removes or processes the depleted reactants, products, and heat [13]. A complete SOFC system is generally composed of fuel processing units, fuel cell stack(s) – combined in a varying number of cells or stacks that match a given power requirement, heat exchange equipment, a control system, and power-conditioning units (PCU). The present work is based on the performance of the solid oxide fuel cell combined heat and power (SOFC-CHP) system, built around an intermediate-temperature (IT) direct internal reforming (DIR) SOFC stack, presented in Fig. 1. For the present techno-economic analysis, SOFC-CHP system efficiency-power curves from full to no net power need to be determined. For that purpose, a SOFC system model has been developed using *gPROMS ModelBuilder* 2.3.5 [14].

4.1. Developed SOFC-CHP system model

In short and as can be seen from Fig. 1, the fuel feed is first mixed with steam, after which this mixture is pre-heated and partially pre-reformed before being fed to the anode side of the stack. Air is compressed and pre-heated before being fed to the cathode side of the stack. After the stack, both the fuel and air streams are fed to a burner where any remaining fuel is burned

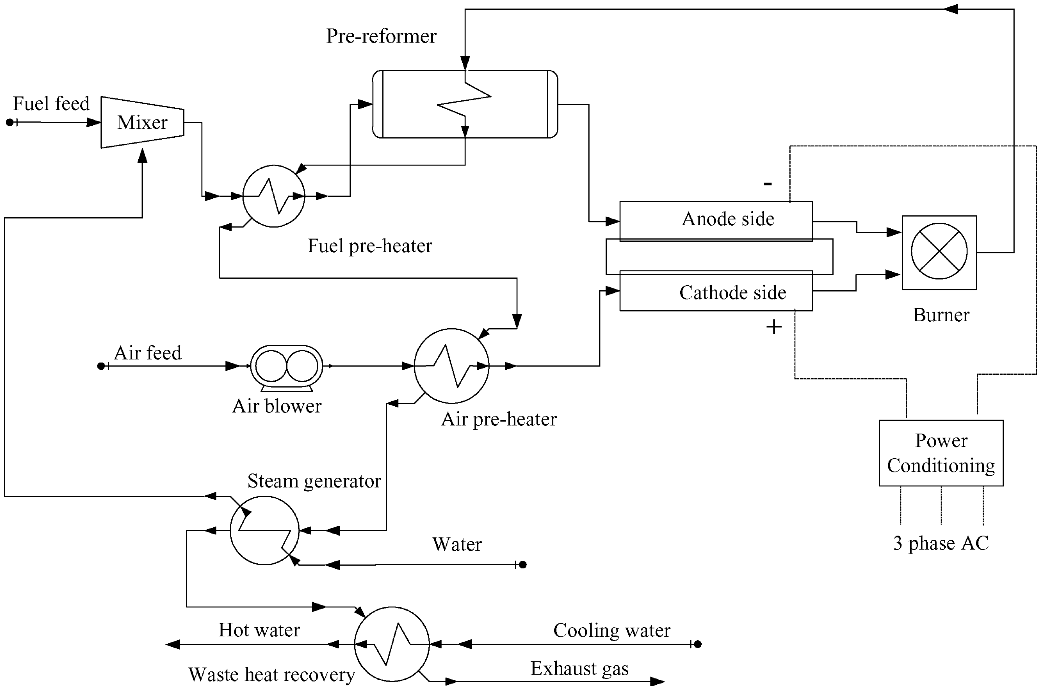

Fig. 1. SOFC-CHP system used in this analysis.

and the resultant hot stream is used to supply heat throughout the system.

4.1.1. Air blower and fuel and air pre-heaters

For the SOFC system in Fig. 1 it is assumed that the fuel is clean methane (desulphurised) and the oxidant is air. The fuel is assumed to be available at sufficient pressure to pass through the system. As for the air stream, this is available at atmospheric pressure and an air blower is thus required. The air blower is an important plant item, as it requires a significant amount of power, due to the large mass of air required to control the stack temperature, and that, if not carefully designed, can affect the overall system efficiency. Fuel and air pre-heaters are required, as the stack (which is at an average temperature of around 1073 K) and the pre-reformer do not tolerate a gas supply at low temperatures. This is because of the excessive cooling and consequent thermal stresses that such cold streams would cause. The two pre-heaters are counter-current heat exchangers that recover heat from the burner exhaust gas to heat the fuel/steam mixture before pre-reforming and the air stream after compression.

4.1.2. Fuel mixer, pre-reformer, and steam generator

The high operating temperature of SOFCs allows for internal reforming to occur directly on the anodes. This represents an advantage of SOFC systems, as the cooling provided by the endothermic reforming reactions reduces the amount of air required for cooling, increasing the system efficiency by reducing the power demand for the air blower. However, as local cooling effects may occur at the fuel channel entrance (as reforming occurs rapidly above 650 °C) and higher hydrocarbons (that can be present in the fuel) tend to decompose at the high stack temperatures, some degree of pre-reforming is recommended. This avoids excessive thermal stresses and possible carbon deposition on the anodes. Thus, a small external pre-reformer is required. A heated pre-reformer has been assumed. This is a combination of a catalytic reactor with a heat exchanger, where the heat necessary for the reforming reactions is provided by the burner exhaust gas. Prior to entering the pre-reformer and the stack, the fuel feed is mixed with steam produced in an external steam generator, again heated by the burner exhaust stream.

4.1.3. SOFC stack

For the SOFC stack, an anode-supported intermediate-temperature (IT) direct internal reforming (DIR) planar co-flow SOFC has been considered. Both steady-state and dynamic studies of such a SOFC stack have been previously performed by the authors [15,16]. While conventional high-temperature SOFCs generally operate between 1073 and 1273 K, a number of research groups are presently focusing on IT-SOFCs. These operate between 823 and 1073 K, allowing for a wider range of materials and cost-effective fabrication, particularly in relation to the interconnections and BoP. High-temperature SOFCs are all ceramic while IT-SOFCs are metal–ceramic and use stainless steel interconnects. As electrolyte-supported cells are only suitable for high-temperature operation, where the often large, ohmic losses can be reduced, electrode-supported SOFCs have been developed to minimise such ohmic losses under lower temperature operation, as in the case of IT-SOFCs. In these cells, one of the two electrodes is the thickest component and support structure, while the electrolyte is required to have high ionic conductivity and/or small thickness.

4.1.4. Burner and waste heat recovery

As is well-known, it is not practical to use all the available fuel in the stack. As this is consumed in the cell, the remaining fuel is progressively diluted in steam and carbon dioxide. Thus, to achieve a reasonable cell voltage and protect the anode from oxidation, a certain minimum hydrogen partial pressure is required, meaning that some residual fuel, determined by the fuel utilisation, is present in the anode exhaust gas. Therefore, a burner is provided after the stack, where the fuel and air stack exhaust streams are mixed and the residual fuel burned conventionally; the residual energy is then used as heat. Finally, in a combined heat and power system recovery of waste heat from the final exhaust gas is essential. Here, the authors assumed that this is used to produce hot water for local space heating.

4.1.5. Control and power conditioning units

In a SOFC system, an effective control strategy normally aims to avoid any possible failure conditions as well as to guarantee that the system responds promptly to any changes imposed. These can include limitations in temperature variation, to avoid thermal stresses in the stack, practical limits on fuel and air flow rates, or a maximum allowable variation of the electrochemical variables. Common requirements for the operation of a SOFC system include: controlling the average stack temperature; assuring that the air ratio always exceeds a minimum specified value; and guaranteeing that the steam to carbon ratio at the entrance of the pre-reformer always exceeds 2.5 to avoid carbon deposition. Stack temperature control is normally provided by varying the air flow rate. However, as the aim of the present publication is not to assess the dynamic behaviour of the SOFC-CHP system proposed, no control strategy is implemented. Ref. [17] provides a more extended study on the control of such a SOFC system. Here, the only characteristics that the system model guarantees are constant fuel utilisation, air ratio and steam to carbon ratio. This means that the flow rates of fuel, water and air are always proportional to the current being drawn to the stack.

Finally, the power conditioning unit, also not included in the present study, is connected to the electrical terminals of the SOFC and has three main tasks: convert the DC voltage from the stack to AC, regulate the voltage (or current) at its own output terminals (to make the electrical power useful to the end user) and prevent any operating condition that may result in damage for the SOFC – this could include limits on current variation with time to avoid excessive changes in voltage. The specific topology of the PCU depends entirely on the application, but in this case it is likely to be a switched-mode power converter [18]. The interested reader may find a model for the PCU and its integration with a SOFC in Ref. [19]. In this work, a specific PCU model is not included, and all the data provided by the SOFC-CHP system model is net DC efficiency data. The power converter efficiency curves reported in Ref. [18] are then used to account for any PCU power losses and, thus, obtain the final

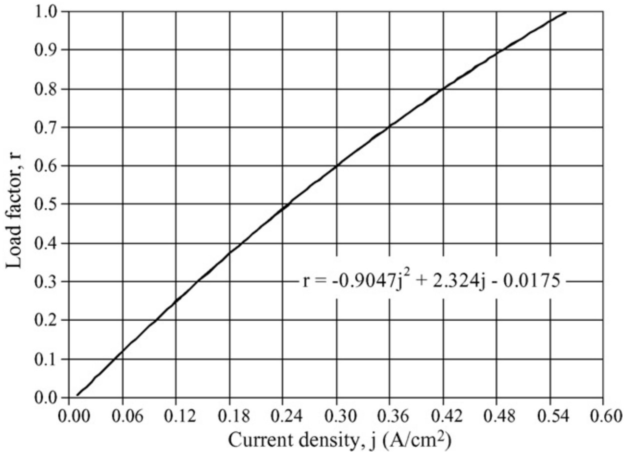

Fig. 2. Load factor vs. current density and corresponding fit function.

net AC efficiency data required in the present techno-economic analysis.

4.2. Electrical, thermal and overall efficiency-power curves

To use the information provided by the SOFC-CHP system model just described in the present design optimisation analysis, it is necessary to express the system electrical, thermal and overall efficiencies as a function of demand (steady-state current load). To do this, a dimensionless parameter, the load factor (*r*), is used. It is defined as the ratio between the system net DC power output and its total capacity. The above model was used to generate data of the various efficiencies as a function of the load factor and of the load factor as a function of the current density for steady-state conditions. Such data was then fitted to appropriate functions that could be integrated into the optimisation problem.

Fig. 2 presents the load factor variation with current density, where a second order polynomial function that fits the data is provided. Fig. 3 presents the variation of the system electrical, thermal and overall efficiencies with the load factor, where sixth order polynomial functions that fit the data are indicated. 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 net DC electrical power is calculated as the total electrical power produced in the stack minus the electrical power necessary in the air blower and an additional constant value that accounts for the electrical parasitic losses in the remaining of the system. The thermal efficiency is the fraction of the chemical energy in the inlet fuel feed that is recovered as heat in the waste heat recovery unit. A constant hot water temperature of 80 °C is specified, achieved by varying the cooling water inlet flow rate. A constant total amount of heat losses is also assumed in the model. The overall system efficiency is the sum of the electrical and thermal efficiencies just defined. The total system capacity used to calculate the load factor is the rated system power. This means that the upper limit of the load factor is 1, as no overload is allowed, while the lower limit is 0, as parasitic loads are taken into account.

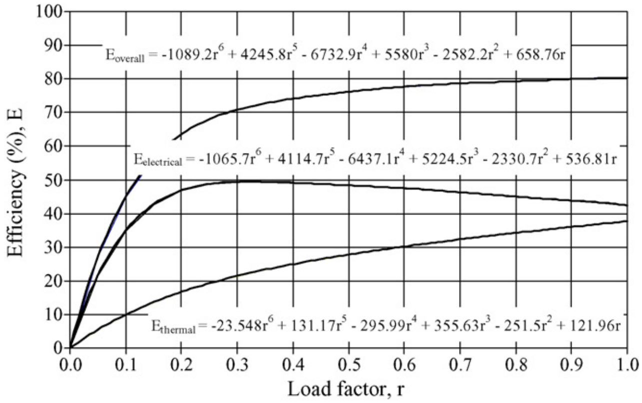

Fig. 3. SOFC system electrical, thermal and overall efficiencies vs. load factor and corresponding fit functions.

The data in Figs. 2 and 3 were generated for a 5 kW rated power system that assumed 200 W of electrical parasitic losses and a total of 200 W of heat losses. The figures were obtained by varying the current drawn from the stack, while maintaining all the remaining inlet conditions fixed: inlet stream temperatures of 25 °C, system fuel utilisation of 70%, air ratio of 7, and steam to carbon ratio at the entrance of the pre-reformer of 2.5. All the remaining input data for the system and stack models can be found in Refs. [17] and [15]. By using such curves in the present analysis, the authors are assuming that, within the range of micro SOFC-CHP systems under study, the system behaviour scales linearly, though it is recognised that this could imply some over-exaggeration of the system performance at the lower power end.

Fig. 2 shows the relationship of the load factor with the current density in the stack and how this decreases when the current drops. This curve is very similar to a typical power–current curve for a SOFC stack except that in this case some current is still required when the load factor reaches zero to account for the fixed parasitic losses. Fig. 3 illustrates the efficiency curves for a complete SOFC-CHP system. Note that, while in a stack electrical efficiency curve, the electrical efficiency increases as the load factor decreases due to the increasingly lower voltage losses observed for lower current densities [18], in a system electrical efficiency curve there is a point after which the electrical efficiency drops rapidly as the system parasitic losses become dominant. The same is observed for both the thermal and overall efficiencies as the surplus of heat that can be recovered decreases.

5. Modelling UK residential heat demand

A dynamic building simulation computer program, TAS from EDSL [20] was used to generate detailed hourly demand profiles for a nominal home heated with different methods. These heat demand profiles were then used as inputs for the modelling section of this paper.

Current UK building regulations [21] specify in detail thermal conductivity of various building elements permitted to be used in new build housing. Ventilation rates are also specified, the aim of the building regulations is to ensure a continuing

Table 1
Building description

Ground floor	Kitchen, two reception rooms, one toilet
First floor	Two bathroom, one toilet, three bedrooms
Roof	Pitched roof, with unheated attic space
	Each room is considered as a zone
Material description	Each major room has at least one window
	Each internal door considered as open with a fraction 0.1
	Air infiltration throughout = 0.5 air changes hour^{-1}
	Single glazing throughout
	No curtains throughout
	Walls are cavity walls (with 50 mm air gap)
	Roof space heavily insulated (200 mm of insulation)

Table 2
Occupancy schedule information

Winter	1 January–30 April and 3 September–31 December	Heating hours: weekdays: 6:00–9:00, 18:00–23:00; weekends: 8:00–23:00; major zones heated to 25 °C
Summer	1 May–2 September	No heating: windows open in a room if the zone temperature > 21 °C and shut > 26 °C

progress towards lower energy homes, while keeping the indoor environment healthy with sufficient fresh air supply. New build homes however only make up a tiny percentage of the overall UK building stock so to model a more typical house requires using less stringent specifications for materials.

A design of home that was considered to be widespread in the building stock and also that had sufficient demand to merit the use of SOFC technology was chosen. The characteristics of the base house can be seen in Table 1.

To model a slow response heating system such as underfloor heating an extra zone was used underneath the floor and the heat load required to keep the room above at the relatively high resultant temperature of 25 °C was registered as the heat demand.

Dwelling size was derived from work carried out by colleagues at the Bartlett [22]. The English House Condition Survey [21] indicates that the national average floor area is 85 m^2, with nearly half of the southern England housing stock containing three bedrooms. The dwelling model assumes two storeys with three bedrooms and a floor area (ground and first floors) of about 75 m^2. The exact dimensions were closely based on the He et al. study [22]. The dwelling was assumed to have the living room and main bedroom facing south. The living room had a floor area of almost 16 m^2 and the main bedroom of 9.4 m^2. The infiltration rate was assumed to be 1 air change per hour, which corresponds to a typical house with original single glazing. In all cases the heating was assumed to provide a resultant temperature of 25 °C during heating hours. The second reception room, the lobby and corridor areas were considered unoccupied and unheated. In reality the heating might be on at similar levels to the sitting room but at different occupancy levels. The overall effect on energy consumption was considered appropriate in this case.

Internal heat gains are also based on He et al. [22], with occupancy at 2.5 persons, lighting set to be on in the late evenings and early mornings with the exact occupancy schedules as shown in Table 3. The assumed profiles remain the same for all four cases considered in this article.

The resulting base model can then be compared with models employing different types of heating system which in turn will generate different demand profiles. Four models were run,

1. Case 1: base model with assumed ideal central heating operating at the hours specified in Tables 2 and 3.
2. Case 2: base model with ideal underfloor heating operating in the same hours as case 1.
3. Case 3: base model with ideal underfloor heating operating constantly in winter.
4. Case 4: base model with 3 kW underfloor heating system operating constantly in winter.

The base case has been deliberately modelled as a typical example of what might be found in the housing stock of the UK. There are many homes that are better insulated and better maintained, but the model considered here is an example of slightly above-average efficiency, with annual heat demand approximately 10% below UK domestic average. New or refurbished energy efficient homes could be expected to have a similar profile of energy use but of a different magnitude.

The resulting space heating demand profiles are displayed in Fig. 4 for 1 day in winter, for cases 1 and 4. The "slow"

Table 3
Occupancy schedules by hour of day

Room (h^{-1})	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Bathrooms							X	X											X		X	X	
Main bedroom	X	X	X	X	X	X															X	X	X
Bedroom 2	X	X	X	X	X	X															X	X	X
Bedroom 3																							
Sitting room (week)						X	X	X									X	X	X	X			
Sitting room (weekends)								X	X	X								X	X	X	X	X	
Kitchen (week)							X										X	X					
Kitchen (weekends)								X	X			X	X	X				X	X				
Heating (weekdays)						X	X	X										X	X	X	X	X	
Heating (weekends)								X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	

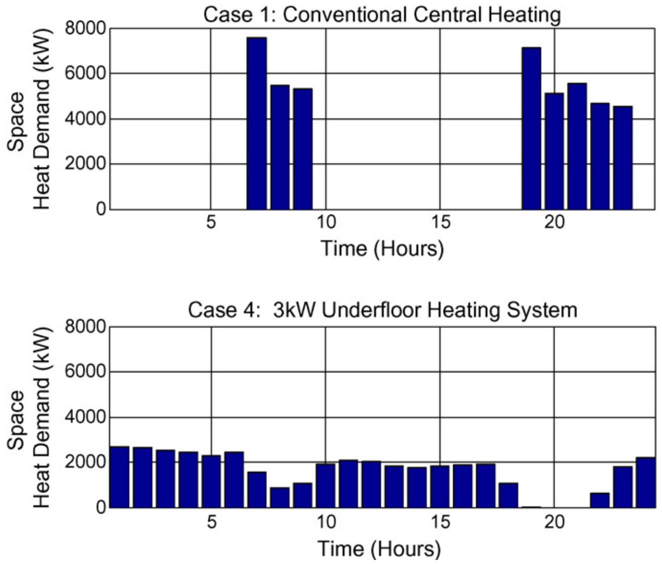

Fig. 4. Comparison of space heat demand profiles for cases 1 and 4.

nature of heating in case 4 is apparent, as this case requires more constant heating with relatively small peak demands as opposed to heating with significant thermal capacity demands in case 1.

6. CODEGen cost minimisation model and input parameters

6.1. *The addition of thermal energy storage to CODEGen*

The model presented here is an extension of the CODEGen (Cost Optimisation of Decentralised Energy Generation) model that has been presented and applied in several other studies [3,18,23–25]. Only a basic description of the existing model is supplied here and the reader should refer to the reference works for a complete description.

The purpose of the model is to identify the minimum equivalent annual cost (EAC), and corresponding "optimum" CHP capacity and "optimum" supplementary boiler capacity of meeting a given energy demand profile. Equivalent annual cost is defined as the cost year^{-1} of purchasing electricity, fuel, and maintenance, plus the equivalent annual cost of owning the micro-CHP system (i.e. the equal annual payments that will cover the capital cost of the system, under a given cost of capital, over its lifetime). Further details of equivalent annual cost can be found in Brealey and Myers [26]. The model can optimise the SOFC stack electrical generation capacity and/or the supplementary boiler thermal capacity along with the operating point for each time period analysed (design optimisation). Alternatively, the system capacities can be fixed and the operating point for each time period optimised (dispatch optimisation).

The addition of thermal energy storage (TES) to the system adds an additional level of complexity to the problem. As with SOFC electrical generation capacity and supplementary boiler thermal capacity, the capacity of the TES must be a decision variable in the optimisation. Additionally there are a number of varieties of TES that vary not only according to the material used (e.g. water, brick, etc.) but also according to the method of charging, discharging, predilection for stratification, etc. Each TES is governed by specific thermodynamic equations and it is expected that these equations vary significantly amongst types of TES. In order to simplify and linearise the problem in this instance we assume a mixed well insulated hot water storage tank. Hot water is delivered to the tank and returned on demand (i.e. the tank is not always full as with some TES systems). Turn-around efficiency is assumed to be 81% (90% charge, 90% discharge), which is a conservative estimate considering the additional constraint that the TES can only store heat for use in the present day, and well insulated tanks generally lose less than 1 °C h^{-1}. The TES energy supply can be used to meet either domestic hot water (DHW) or space heating demands, which is unusual for the UK, but not uncommon in other parts of Europe.

Therefore, in order to model the TES in CODEGen, we require two additional decision variables (X) for charge and discharge for each time period, and one decision variable for the capacity of the TES (kWh). We add the charge/discharge variables to those defined in [23] as follows:

$$X_{5,1} = \text{TES charge in time period 1 (kWh}_{\text{th}}\text{)},$$
$$X_{6,1} = \text{TES discharge in time period 1 (kWh}_{\text{th}}\text{)}.$$

These two variables are applied to each time step. For a problem with n time steps this creates an additional $2 \times n$ decision variables in the problem. The decision variable for the capacity of the TES is added to the other capacity variables defined in [23] as follows:

$$X_{n+2} = \text{TES capacity (kWh}_{\text{th}}\text{)}.$$

The objective function, which represents the equivalent annual cost of meeting the energy demand profile remains the same as [23] except for the addition of a term for the annualised capital cost of the TES plus a maintenance cost (either annual of kWh^{-1} discharge).

Likewise the constraints in [23] remain the same, and new constraints are added. These serve the following purposes:

- Respect the TES capacity for every time period. The amount of stored energy cannot exceed the systems capacity, and cannot be less than zero.
- The amount of energy drawn from the TES must be less than the available energy in the TES at that time.
- The amount of energy in the thermal store at midnight must always be zero. This prevents energy transfer between "days" in the analysis,[2] which strengthens the efficiency assumption and allows analysis using representative sets of days (i.e. prevents energy transfer between seasons, etc.).

We use a number of "typical" days to represent the annual energy demand profile. Each day is weighted according to how

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[2] As we use a subset of days to represent a whole year, we must prevent TES transfer from 1 day to another because this would equate to transfer of heat between seasons, which is not possible.

Table 4
Selected input parameters

Parameter name	Parameter value and units
SOFC electrical efficiency[a]	$\eta_{el} = -10.657r^6 + 41.147r^5 - 64.371r^4 + 52.245r^3 - 23.307r^2 + 5.3681r$
SOFC overall efficiency (heat + power)	$\eta_{overall} = -10.892r^6 + 42.458r^5 - 67.329r^4 + 55.8r^3 - 25.822r^2 + 6.5876r$
SOFC stack capital cost	£333 kW_e^{-1} + £333
SOFC annual maintenance cost	£20 $year^{-1}$
SOFC lifetime	10 years
SOFC rate of change of current density limit	0.05 $A\,cm^{-2}\,min^{-1}$
SOFC minimum net electrical output	20% of capacity
TES charge efficiency	90%
TES discharge efficiency	90%
TES annual maintenance cost	£10 $year^{-1}$
TES capacity	12 kWh
Boiler efficiency	86%
Boiler capital cost	£10 kW^{-1} + £1463
Boiler annual maintenance cost	£45 $year^{-1}$
Boiler lifetime	10 years
Boiler minimum capacity	10 kW
Residential electricity tariff[b]	8.39 pence kWh^{-1}
Residential gas tariff[b]	2.11 pence kWh^{-1}
Electricity buyback rate[c]	4.0 pence kWh^{-1}
Annual electricity demand for average dwelling	4350 kWh_e
Annual space heat demand for the dwelling	Case 1: 13,612 kWh Case 2: 12,982 kWh Case 3: 14,328 kWh Case 4: 12,081 kWh
Emissions rate for grid electricity	0.43 kg CO_2/kWh
Emissions rate for natural gas	0.189 kg CO_2/kWh
Discount rate for capex	12%

[a] The variable, *r*, is the instantaneous load factor (net stack output divided by maximum stack output).

[b] Electricity and gas costs are based on Q1 2006 average residential energy price for a medium dwelling [28].

[c] Electricity buyback rate is based on the average UK wholesale price of electricity, rounded up to the nearest penny to reflect government incentives supporting micropower and low carbon generation (e.g. the energy efficiency commitment).

many days there are of a particular type in the year, and a fine temporal precision is employed in accordance with the findings in previous studies [25].

6.2. *CODEGen input parameters*

Input parameters applied, along with estimates of their values are presented in Table 4. Electricity demand profiles employed are the result of the DTI domestic photovoltaic field trial, and thermal demand profiles employed are the four cases discussed above. Domestic hot water (DHW) demand is added to each of the four space heating cases based on measured data of the Solar Trade Association Croydon [27].

7. Analysis, results and discussion

The four heat demand profiles developed in Section 5 are coupled with an average UK residential electricity demand profile. For each of the four cases, baseline equivalent annual cost and CO_2 emissions are calculated based on meeting all electricity requirements with UK grid-average power, and meeting heating requirements with natural gas burned in an 86%-efficient condensing boiler.

Table 5
Baseline result for each of the four modes of space heating, where all electricity requirements are met with grid-average electricity, and heat demands are met by an 86% efficient condensing boiler

Space heating case	EAC (£ $year^{-1}$)	CO_2 emissions (kg CO_2 $year^{-1}$)	Boiler capacity (kW)
Case 1	963	5100	16
Case 2	949	4976	16
Case 3	988	5326	16
Case 4	924	4809	10

For each of the four heat demand cases (cases 1–4 from Section 5) the CODEGen model is then applied to determine the optimum SOFC-system capacity and the corresponding minimum equivalent annual cost (EAC) of meeting the energy demand profile, and the CO_2 emissions associated with the minimum EAC. The systems analysed in this model run do not incorporate thermal energy storage.

Thermal energy storage is then added to the system, and EAC and emissions recalculated for each of the four cases as per the previous model run. Results are compared and discussed.

The baseline results indicate slight difference in EAC and emissions, as is expected for the different modes of heating and different resulting overall annual heat demand for each case. The boiler thermal capacity required decreases for the “slower” heat demand. The baseline results are presented in Table 5.

In comparison with the baseline results, the addition of a SOFC-based micro-CHP system (Table 6) provides an economic benefit in three out of four cases, and a comparable result in the other (case 2—ideal underfloor heating with low operating hours). However, in all cases the micro-CHP unit delivers a carbon dioxide emissions reduction between 140 and 760 kg CO_2 $year^{-1}$.

As is apparent from Table 7, the addition of thermal energy storage (TES) further improves the economics and emissions reduction of the SOFC system, although this study assumes that the TES is already present in the house (i.e. no capital cost),[3] which is not true in all cases. It is also noted that TES systems impose possibly significant space penalty, and are therefore not appropriate in many cases, particularly smaller dwellings. As expected, TES is less effective in case 4 (£22 $year^{-1}$ benefit, as opposed to £43 $year^{-1}$ with case 1) where the heat demand is relatively evenly distributed which implies that there is less economic benefit to be gained from the ability to decouple heat supply and heat demand. However, substantial emissions benefit is obtained from case 4 “slow” heat demand and TES, with more than 1 tonnes $year^{-1}$ CO_2 emissions reduction over the baseline case 4 scenario.

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[3] The TES system considered has a capacity of 12 kWh, and a lifetime of 25 years. Based on commercial data, a system like this has an equivalent annual capital cost of £64/year at the 12% discount rate applied in this study.

Table 6
Results for SOFC-based micro-CHP system without thermal energy storage

Space heating case	EAC (£ year^{-1})	CO_2 emissions (kg CO_2 year^{-1})	Boiler capacity (kW)	Optimum SOFC system net electrical capacity (kW$_e$)
Case 1	947	4805	15	0.74
Case 2	952	4832	15	0.66
Case 3	978	4987	15	0.75
Case 4	888	4047	10	1.06

Table 7
Results for SOFC-based micro-CHP system with thermal energy storage

Space heating case	EAC (£ year^{-1})	CO_2 emissions (kg CO_2 year^{-1})	Boiler capacity (kW)	SOFC system net electrical capacity (kW$_e$)	Thermal energy storage capacity (kWh)
Case 1	904	3985	10	1.3	12
Case 2	916	4353	11	0.9	12
Case 3	929	4296	10	1.2	12
Case 4	866	3695	10	1.3	12

Fig. 5 displays the CO_2 emissions reduction and corresponding equivalent annual cost saving (over the baseline result for each case) for each of the four heating scenarios with optimised SOFC stack capacity, with and without thermal energy storage (TES) present in the system. Case 4 “slow heating” provides significant CO_2 emissions reduction at negative cost (i.e. the system saves money and reduces carbon dioxide emissions). This result applies in situations with and without TES. Case 1 with TES is also a strong contender, with a large cost saving, and the best emissions reduction result. However, if the technical consideration where the avoidance of thermal and load cycling is taken into account, it appears that the more constant heat demand (case 4) provides the best result for SOFC-based micro-CHP technology in that it is economically and environmentally comparable, but provides for more consistent output from the micro-CHP unit (see Fig. 6), which is a better match for SOFC-based technology than load cycling.

Fig. 7 shows the equivalent annual cost (EAC) of meeting electricity demand and heat demand as per case 4. Fig. 7 displays two scenarios with optimised SOFC stack capacity and two cases where a fixed 2.0 kWe stack is considered. The associated annual carbon dioxide emissions reduction is also plotted, along with

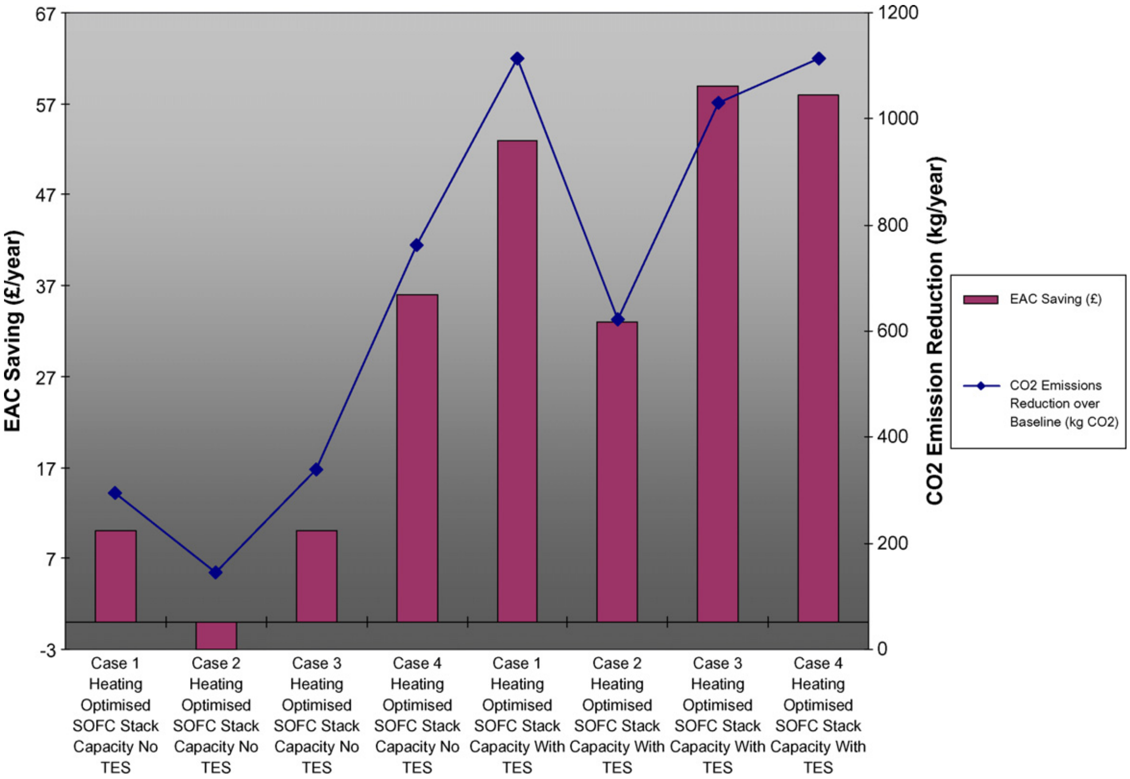

Fig. 5. CO_2 emissions reduction and annual cost saving for the four cases of heating with and without thermal energy storage (TES).

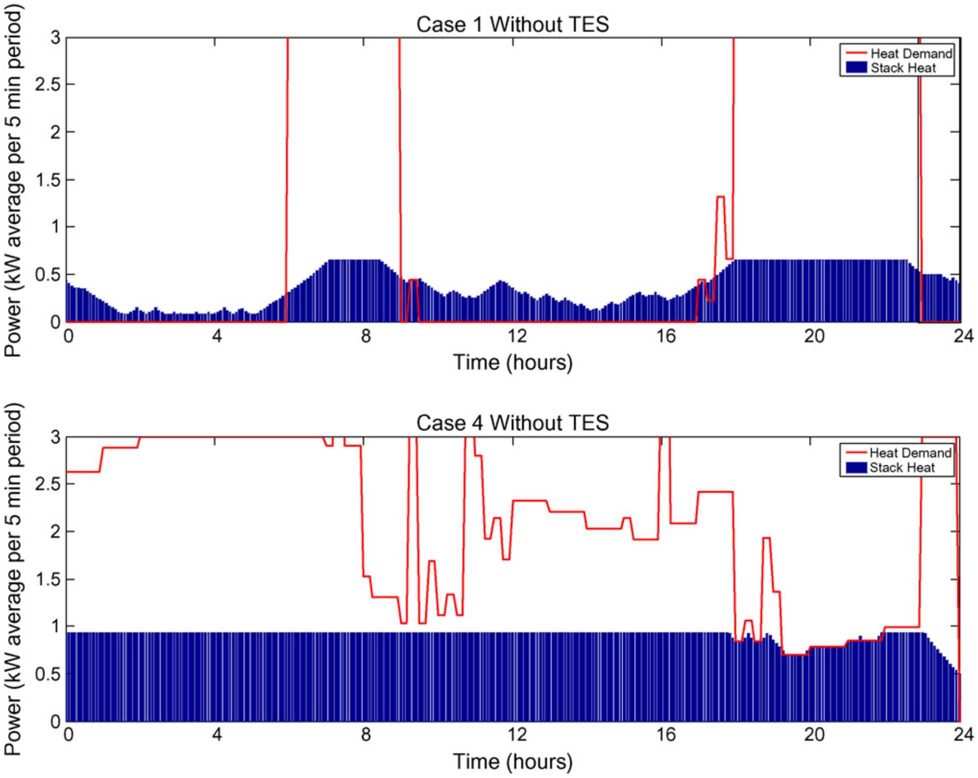

Fig. 6. Heat demand and SOFC-stack heat output for case 1 without TES and case 4 without TES; case 4 exhibits a constant optimal output from the stack, whilst case 1 exhibits load cycling.

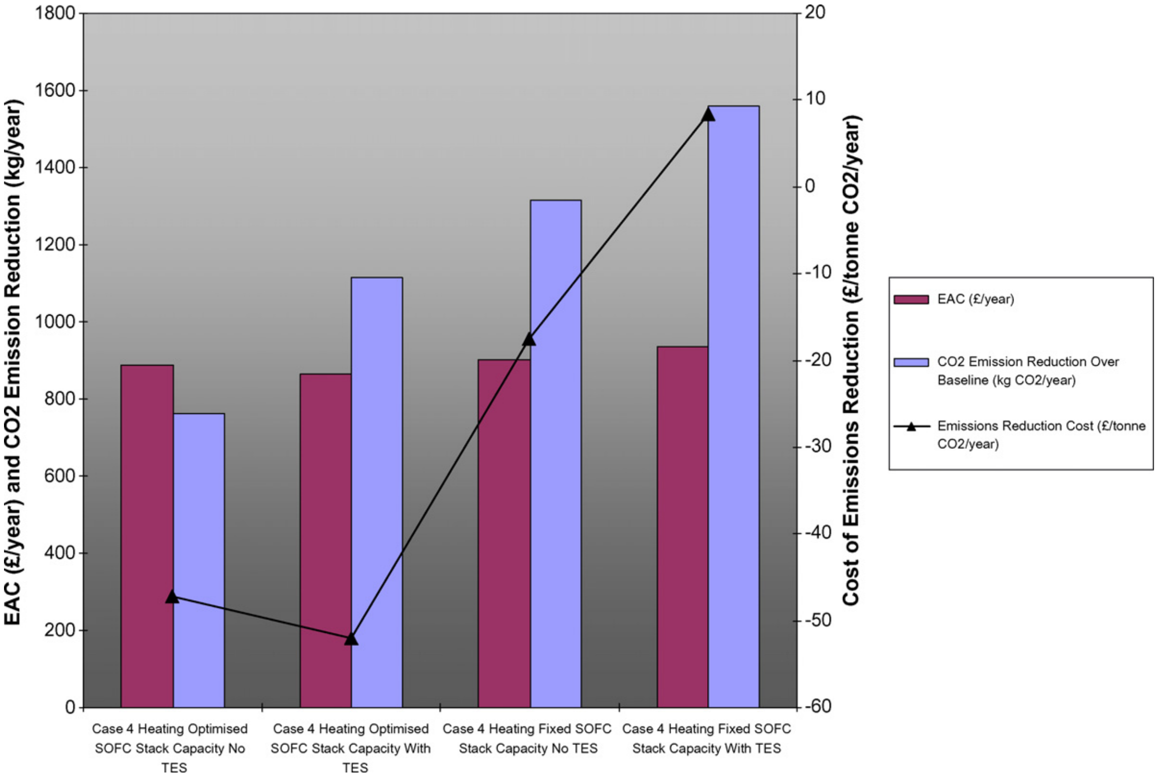

Fig. 7. Equivalent annual cost, CO_2 reduction, and CO_2 reduction cost for case four heating scenario demand with optimised vs. 2 kWe SOFC-stack electricity generation capacity.

the cost tonnes^{-1} of reduction (calculated by determining the extra cost of each scenario over the baseline scenario, and dividing by the associated emissions reduction). The EAC of each scenario for case 4 heating is roughly equivalent, but emissions reduction varies significantly between the cases. Subsequently, cost of emissions reduction also varies significantly, with the first three scenarios showing negative cost of CO_2 reduction, and the forth case displaying a small cost of emissions reduction.

With the current price of carbon dioxide in the European Union Emissions Trading Scheme at approximately €16 tonnes^{-1} [29], even the cases where the cost of meeting energy demand increases (e.g. fixed capacity with TES case in Fig. 7) are potentially acceptable because the cost of the emissions reduction is cheaper than buying credits on the market.

8. Conclusion

This article has presented a solid oxide fuel cell (SOFC) based micro combined heat and power (micro-CHP) system model for use in a techno-economic analysis of some options for provision of residential heat demand in the UK. Four heat demand profiles were developed based on different options for heating of residential dwellings, with the aim of determining which profile is best suited to the CHP system. Thermal energy storage (TES) was also considered as one of the heating options, and an existing energy cost minimisation model (CODEGen) was altered to include TES. The SOFC-based micro-CHP model and thermal demand profiles (and other input parameters) were input to the cost minimisation model to determine the minimum cost of meeting energy demand in each case, with and without thermal energy storage.

It was found that a slow space heating demand, based on a 3 kW underfloor heating system running constantly in winter, was most suitable for coupling with the micro-CHP system. This is because it provided a good economic result, and substantial CO_2 emissions reduction when compared with the baseline scenario where all electricity needs were met from the grid and heat needs were met by burning gas in a condensing boiler. Additionally, the slower heating demand is a better technical match for SOFC technology, which benefits from the avoidance of load and thermal cycling. The addition of thermal energy storage provided some further economic benefit where the dwelling already has such a system in place, and achieved additional emissions reduction benefit.

Conventional central heating systems were also considered in the analysis. The CHP system was also economically viable in this case and benefited more than other cases from the decoupling of heat supply and heat demand provided by TES. Emissions reduction resulting from the system considered in this case was not as significant as that achieved by slower space heating outlined above.

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