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Solid oxide fuel cell systems for residential micro-combined heat and power in the UK: Key economic drivers☆

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Abstract

The ability of combined heat and power (CHP) to meet residential heat and power demands efficiently offers potentially significant financial and environmental advantages over centralised power generation and heat-provision through natural-gas fired boilers. A solid oxide fuel cell (SOFC) can operate at high overall efficiencies (heat and power) of 80–90%, offering an improvement over centralised generation, which is often unable to utilise waste heat. This paper applies an equivalent annual cost (EAC) minimisation model to a residential solid oxide fuel cell CHP system to determine what the driving factors are behind investment in this technology. We explore the performance of a hypothetical SOFC system—representing expectations of near to medium term technology development—under present UK market conditions. We find that households with small to average energy demands do not benefit from installation of a SOFC micro-CHP system, but larger energy demands do benefit under these conditions. However, this result is sensitive to a number of factors including stack capital cost, energy import and export prices, and plant lifetime. The results for small and average dwellings are shown to reverse under an observed change in energy import prices, an increase in electricity export price, a decrease in stack capital costs, or an improvement in stack lifetime.

Keywords: SOFC; CHP; Decentralised; Optimisation; Capital cost; Lifetime; Electricity export

1. Introduction

This paper is published against a backdrop of great interest in decentralised power generation in the UK and internationally. The recent Energy White Paper released by the UK Government [1] notes that in order to improve reliability of the energy supply system it would be advisable to include distributed energy sources in the energy mix. Additionally, the White Paper suggests a 60% CO_2 reduction target by the year 2050. This is a challenging objective that could be aided through the introduction of more low carbon generation, including decentralised energy systems. Several countries around the world are implementing programs to aid decentralised generation. In the USA substantial headway is being made towards a target of 92GW combined heat and power (CHP) by 2010, which would correspond to a doubling of capacity since 1998. This program is justified as a response to energy price spikes, power outages, power quality problems, dirty air, and global climate change [2]. Internationally, decentralised energy is perceived to assist in meeting energy security and environmental concerns, and is often economically competitive with centralised generation technologies [3]. Residential micro-CHP, the subject of this paper, is an emerging decentralised energy technology that can contribute to these broad environmental, economic and security aspirations.

A common question put forward by micro-CHP designers and manufacturers is “what kWe capacity should our generators be for the residential market” and “what are the key economic drivers and sensitivities behind this decision?” The answers to this question provide valuable input to system design and control, and allow further research to be directed at the areas that can provide the greatest economic benefit to

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users of the technology. Therefore, the aims of this paper are: to describe a model designed to explore the economic characteristics of emerging decentralised energy technologies; to apply this to investigate the optimal generation capacity (i.e. capacity that results in minimum cost to the user) and dispatch strategy of a solid oxide fuel cell (SOFC) CHP system for the UK residential market; and to determine the primary driving factors behind the investigation results in order to assess what factors may realistically be improved in the medium term to advance the prospects of the technology.

The economic/technical factors analysed in this study are stack capacity, stack capital cost, stack lifetime, stack electrical efficiency, electricity export price, and energy import prices.

2. Solid oxide fuel cell systems

In order to arrive at relevant input parameters for our analysis, we perform a literature review of the various costs and technical characteristics associated with SOFC systems.

A number a varieties of fuel cells are currently available or in the demonstration phase. Polymer electrolyte fuel cells (PEFC), alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC), molten carbonate (MCFC) and solid oxide fuel cells are all competing for various niches. Of these technologies, PEFC and SOFC technologies appear to offer the greatest potential for small-medium scale CHP systems. This study focuses on SOFC technology for the reasons outlined below.

The solid oxide fuel cell is an emerging technology with the ability to provide combined heat and power at an electrical efficiency between 40 and 55%, and an overall LHV efficiency between 80 and 90%. The heat provided by a SOFC is high-grade, typically at greater than 800 °C, although it should be noted that intermediate temperature SOFCs are being developed that operate between roughly 550 and 800 °C. Perhaps the most compelling factor driving the R&D efforts being directed at SOFC power systems as opposed to PEFCs is that they can be directly fuelled by natural gas—a convenient and readily available fuel in many countries in the world.

These characteristics make SOFCs an ideal candidate for many scales of CHP: a brief market analysis shows SOFC systems being demonstrated in capacity ranges from 1 kWe by Sulzer Hexis [4] through to 250 kWe by Siemens Westinghouse [5]. Although scale-up of SOFC technology is yet to be tested, there is no indication that these figures represent capacity limitations for SOFCs.

SOFCs are not without their limitations, which relate primarily to their high operating temperatures. Thermal stresses within the cells during start up and across cells during operation lead to mechanical failure of components at their interfaces, suggesting a lifetime of roughly 5 years at full load given the current technology. Additionally, the balance of plant (BoP) in the CHP system must be constructed from relatively expensive materials in order to withstand the high operating temperature, and complex thermal management techniques must be applied for efficiency and to ensure safety of the system in a residential environment.

From an economic perspective, SOFC systems appear to be very promising. Rolls Royce recently suggested that capital costs of US\$300 kWe^{-1} [6] are already achievable for large SOFC-gas turbine hybrid systems. Although the literature varies in estimate of costs from US\$300 kW^{-1} to US\$20,000 kWe^{-1} [7], the majority of estimates are in the range of US\$700 [8] to US\$1300 kWe^{-1} [9]. Given the relative immaturity of SOFC technology, significant cost reductions can be expected through both further technological development and learning-by-doing. Operation and maintenance costs of SOFC technology are currently high, at around US\$0.025 kWh^{-1}. Again this is attributable to relative immaturity, and it is asserted that this could be driven down to around US\$0.01 kWh^{-1} [7].

The rate at which power output from an SOFC can be varied is limited by thermal stress considerations. SOFC construction requires binding together materials with dissimilar thermal properties. As the cell is heated to its operating temperature thermal stresses appear between the materials. Additionally, temperature across the cell can vary, inducing further thermal stress. The production of materials to address these issues is currently the focus of much research.

Given these thermal stresses, the endurance of SOFCs is of particular concern, but prospects are encouraging. Current large-scale tubular SOFC technology has been proven to operate for approximately 40,000 h with less than 0.2% voltage degradation per 1000 operating hours. This corresponds to approximately 5 years of continuous operation. Older tubular SOFC technology has been proven to operate for roughly 70,000 h with less than 0.5% voltage degradation per 1000 operating hours, and this technology has since been improved, suggesting that more than 70,000 h of operation is possible where some voltage degradation is acceptable [8].

Conventional generating technology usually exhibits a decrease in efficiency as load is reduced from the maximum. Similarly to all fuel cells, SOFCs exhibit the characteristic of high part load efficiency; as the SOFC approaches its maximum capacity, concentration, activation, and ohmic polarisation changes serve to decrease its efficiency. This characteristic is potentially useful for low load-factor residential applications. Efficient part load operation could allow installation of a larger fuel cell generator than for competing technologies, increasing the share of demand met on-site.

The maximum efficiency gains of decentralised CHP over centralised generation and onsite boiler combinations can only be achieved when little energy is discarded from the system. A rapidly variable heat-to-power ratio is desirable when considering a single dwelling or small group of dwellings. This concept, and the pinch point design of a PEFC CHP system to meet this need, have been investigated by Colella [10]. Fuel cell technology offers an advantage over its competitors in this regard. The ability to produce electricity efficiently, combined with the potential for waste-heat recovery in a hot

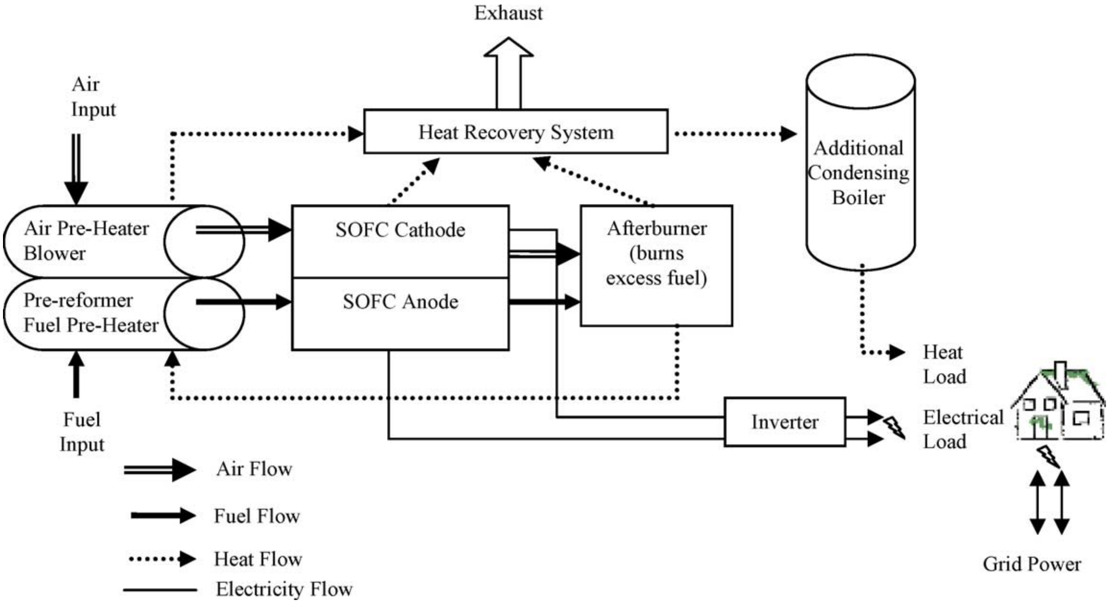

Fig. 1. Simplified SOFC CHP system.

water storage tank, allows a wider range of heat-to-power ratios to be met more efficiently than conventional CHP.

3. Decentralised generation equivalent annual cost (EAC) minimisation model

3.1. Model concept

The purpose of the model is to identify the minimum equivalent annual cost (in UK pounds), and corresponding "optimum" SOFC stack capacity (kWe) and supplementary boiler capacity (kWth), to meet a given energy demand profile. The system is optimally dispatched (i.e. dispatched to provide minimum energy cost) and is grid-connected. Equivalent annual cost of meeting energy demand is defined as the equivalent cost per year of owning the micro-CHP/boiler system over their entire lives, plus the cost per year of providing whatever fuel and electricity is necessary meet energy demands in the dwelling. It is necessary to use equivalent annual cost in this study rather than net present value as the CHP unit and supplementary boiler can have different lifetimes. The optimisation performed can choose optimum capacities of the SOFC and of the additional boiler, along with the operating regime or point for each time period,[1] or can choose the optimum operating regime for each time period for a given fixed capacities of the SOFC and additional boiler.

The technical CHP system modelled is an anode supported intermediate temperature direct internal reforming solid oxide fuel cell micro-CHP system operating in parallel with the electricity grid. Electricity can be bought from and sold to a supplier, and natural gas can be imported from the piped network. An additional boiler is also included in the micro-CHP system to provide any supplementary heat required, and meet any rapidly fluctuating heat loads that the fuel cell is unable to respond to. This system, including a basic depiction of balance of plant, is represented diagrammatically in Fig. 1.

The specifics of the SOFC stack, which is the technical focus of this study, are described in further detail in Section 4.

3.2. Model Structure: CODEGen

The CODEGen model, for the cost optimisation of decentralised energy generation, has been developed to analyse this system. As discusses in Section 3.1, it minimises the equivalent annual cost of meeting a given electrical and heat load though consideration of CHP and boiler system capacities to be installed, and how to dispatch system components according to price and demand signals. For each time period considered, the system has six cost drivers: the cost of fuel to run the fuel cell; operation and maintenance of the fuel cell; the cost of fuel to run the additional boiler; operation and maintenance of the boiler; the cost of imported electricity, and the revenue from any electricity sold to the grid. For each time step we have four decision variables that reflect these cost drivers.

1) $x_{1,1}$ = onsite electricity generation used onsite (time period 1);
2) $x_{2,1}$ = imported electricity from the grid for onsite use (time period 1);

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[1] Operating point is defined as SOFC power and heat generation for onsite use, SOFC power generation for sale to the grid, imported natural gas for the additional boiler, and imported power from the grid.

3) $x_{3,1}$ = imported natural gas for use in a separate boiler (time period 1);
4) $x_{4,1}$ = exported electricity (time period 1).

These four optimisation variables apply to each time step from $i = 1 - n$, where n is the total number of time steps in the analysis period. In addition to these $n \times 4$ optimisation variables, we have two additional cost drivers—the installed capital cost of the SOFC and the installed capital cost of the additional boiler, reflected through the two decision variables:

$(n \times 4 + 1)$ x_n = SOFC rated capacity;
$(n \times 4 + 2)$ x_{n+1} = boiler rated capacity.

The objective is to minimise the equivalent annual cost of meeting a given set of power and heat demands, which includes the annual cost of owning the CHP/boiler system over its entire lifetime. Eq. (1) is a basic representation of the objective function.

$$\text{EAC} = (\text{annual fuel and O\&M cost for onsite generation (including heat)} + \text{annual cost of buying imported electricity} + \text{annual cost of imported natural gas for the boiler} - \text{annual revenue from electricity sold to the grid}) + \text{equivalent annual capital cost of SOFC and additional boiler.} \quad (1)$$

The objective function is subject to constraints:

- Overall, the given power and heat demands must be satisfied. The heat demand may be exceeded by a specified amount, limited by the technical constraint for heat dump from the system.
- Neither SOFC nor boiler output can exceed their rated capacities. One may explicitly limit the stack and boiler capacities, or allow the optimiser to choose these capacities.
- Thermal stresses within the SOFC prevent rapid changes in power output, so power output in each time period is limited to be within a specified range of the power output for the previous time period.

We use a number of “typical” days of energy demand data at fine (i.e. 5 min) temporal precision, which is required to obtain accurate optimisation results [11]. Each day is weighted according to how many days there are of that type in each year.

3.3. Model implementation

The model developed uses a sparse sequential quadratic programming optimisation method to minimise the equivalent annual cost of meeting the given heat and power demand. The programming language employed is object-oriented C++ in conjunction with the E04UGC routine from the NAG C Library Mark 7.

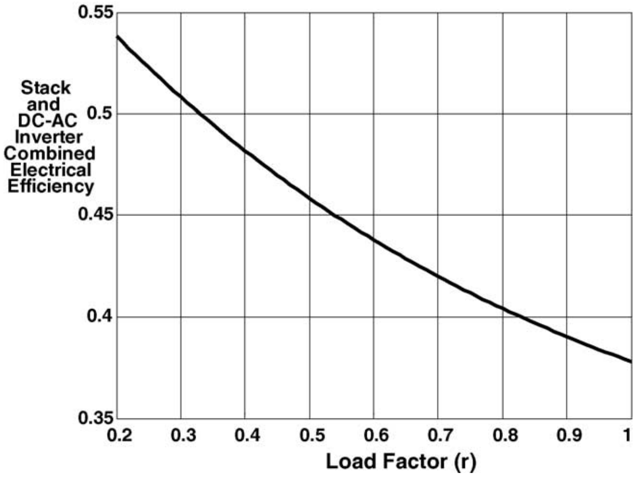

Fig. 2. Combined stack and dc–ac inverter electrical efficiency vs. load factor (load factor is the average electrical output in a time period divided by the maximum electrical output capacity).

4. SOFC high-level characterisation

As apparent from Fig. 1, the electrical output from the SOFC stack is directed through a dc–ac inverter. In order to obtain a high-level characterisation of the system, we must combine the electrical efficiencies of the stack and inverter.

The electrical efficiency profile of the SOFC, given by Eq. (2), was generated from a SOFC model developed by Imperial College London Chemical Engineering department, and exhibits typical high part-load efficiency:[2]

$$\text{Electrical}_{\text{eff}} = -0.0607r^3 + 0.253r^2 - 0.453r + 0.6593, \quad \text{where } r \text{ is the load factor} \quad (2)$$

The dc–ac inverter, which typically incorporates approximately 7% losses at low load factors, and 3% losses at rated capacity [12]. When the stack and dc–ac inverter efficiency profiles are combined, the resulting system electrical efficiency is shown in Fig. 2.

In addition to the system electrical efficiency profile, we assume overall efficiency (heat + power) of the stack is similar to competing boiler technology (circa 90%) and is given by Eq. (3).

$$\text{Overall}_{\text{eff}} = 0.05r + 0.9, \quad \text{where } r \text{ is the load factor} \quad (3)$$

This implies that the system has good heat recovery characteristics, with 90% overall efficiency at minimum load, and 95% overall efficiency at maximum load.

Note that balance of plant consideration relating to the electrical and overall efficiency profile is simplified in this analysis, being reduced to four basic measures to conservatively account for these loads. These are:

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[2] r, the load factor, is defined as the average electrical output (kWe) within a time period divided by its maximum electrical output capacity (kWe).

1. An additional heat load proportional to stack output—to account for fuel and air pre-heating, and pre-reformer loads (set to 10% in this study).
2. An additional electrical load proportional to stack output—to account for blower loads (set to 5% in this study).
3. An additional constant electrical load—to account for control system load (set to 50 W in this study, designed to combine with the boiler control system load already present in the investigated electricity demand profile).
4. System is limited to operate above a load factor of 0.2. Below this level, BoP loads and thermal balancing issues are significant, and our efficiency profile inapplicable.

5. UK residential energy demand and other input parameters

Residential energy demand patterns vary widely, influenced by a complex range of factors such as dwelling size, number of occupants, income, age of occupants, and lifestyle to name a few.

From the point of view of a stack manufacturer, in order to obtain an accurate picture of the optimum stack capacity, it is necessary to first obtain a representative picture of the range of electricity and heat demand profiles of potential customers. In this paper, to capture something of this range, three illustrative demand profiles have been employed relating to small, average and large dwellings for current UK conditions. Each of the electricity demand profiles was measured at a real UK residential property by Building Research Establishment Ltd (BRE), and is summarised in Table 1. The heat demand profiles (also summarised in Table 1) were generated based on an assumed heating cycle (morning and evening heating in winter), and designed to correspond with official consumption statistics (see below) and heat-delivery rate constraints of existing housing stock.

The classification of small, average and large has been derived from official statistics; the building research establishment electricity demand data was compared with Department of Trade and Industry (DTI) statistics to determine what constitutes a "small", "average", and a "large" demand. Likewise, heat demand profiles were generated with the intention of reflecting the UK average and a reasonable variation either side of this average.

The average UK electricity demand is approximately 4675 kWh based on UK totals in DTI [13] and division by the number of UK households according to the UK Census 2001. DTI reports the average domestic gas consumption as 19,358 kWh, of which some 10% is accounted for by cooking [14]. Therefore, the "average" dwelling in Table 1 corresponds reasonably well with the national average whilst the "small" and "large" dwellings exhibit reasonable variation either side of this average. Demand data used in this study consists of 5 min electricity consumption data over an entire year for a range of properties, from which these three scales of total demand (small, average and large) were selected.

Table 1
Basic statistics of selected BRE electricity demand profiles and generated heat demand profiles

Dwelling	Annual electricity demand (kWh)	Annual heat demand (kWh)
Small	2455	15137
Average	4350	17950
Large	7627	24539

As described in Section 3.2, to ease the computational burden the model works with a sample subset of days from the annual demand profile. In this study six sample days are used to represent the annual demand profile (two winter days, two summer days, and two shoulder days) for each dwelling, at 5 min temporal precision.

Other input parameters of interest, with their central estimates, are:

1. Stack capital cost—£333 for any stack above zero kWe plus £333 kWe^{-1} installed. This estimate is based on information presented in Section 2.
2. Boiler capital cost—£1000 for any boiler, plus £50 kWth^{-1} installed, based on installed cost of a variety of advertised systems.
3. Stack lifetime—5 years, based on information in Section 2.
4. Boiler lifetime—10 years.
5. Discount rate—12%, a basic commercial discount rate.
6. Natural gas cost—2.309 p kWh^{-1} for the first 1143 kWh per quarter, 1.453 p kWh^{-1} thereafter, based on London Electricity prices at May 1st 2003.
7. Electricity import cost—10.79 p kWh^{-1} for the first 225 kWh per quarter, 6.38 p kWh^{-1} thereafter, based on London Electricity prices at May 1st 2003.
8. Electricity export price—3 p kWh^{-1}, near the UK average wholesale electricity price.
9. Maintenance—£45/year for the boiler, £20/year for the stack.
10. Maximum heat dump—0.5 kWth, through a fan-assisted flue.
11. Stack minimum output level—0.2 load factor.
12. Boiler minimum capacity—5 kWth, to meet domestic hot water load variations.

These central estimates are only indicators of current market conditions or perceived medium-term estimates of the state of SOFC technology. The SOFC technology described here and in Section 4 is not yet commercially available, with further development required for example to bring costs to the levels projected in Section 2. However, the approach taken in this paper is to model this hypothetical system under the current UK market conditions. This approach avoids introducing potentially confounding factors to the analysis by attempting projections of other input parameters—for example the future trajectories of gas and power prices. Sensitivity analysis is used to indicate the relative importance of the key input assumptions.

6. Results and discussion

Results are presented as follows: we first establish a baseline result corresponding to a dwellings energy requirements being met by grid power and a condensing boiler. We then find which dwellings represent viable micro-CHP investment opportunities under the "central estimate" input parameters presented in Section 5. Sensitivity of the investment decision to six parameters are then explored in the following sections. These parameters are; stack capacity, stack capital cost, stack lifetime, stack electrical efficiency, electricity export price, and electricity/fuel import prices.

6.1. Baseline result

The baseline result in this study is the case where all electricity demands are met by the grid, and all heat demands are met by importing natural gas for use in a 90% efficient condensing boiler. Results for this analysis are presented in Table 2, and are used as a check for other results, in that a viable micro-CHP system must yield a result with either equal or lower equivalent annual cost than this baseline.

6.2. Central estimate result

The central estimates of each input variable and demand profiles presented in Section 5 are input to the CODEGen model, and the stack and supplementary boiler capacities that result in minimum equivalent annual cost are identified. The optimisation results for these input data are presented in Table 3.

From Table 3 it is apparent that the central estimate of input variables results in only the dwelling with large demand choosing to install a SOFC micro-CHP system. However, this decision is marginal as the cost saving between this system and the baseline result (Table 2) is only £16 per year.

Table 2
Grid-boiler baseline result

Dwelling	EAC (£)	Boiler capacity (kWth)
Small	791	11.97
Average	987	14.82
Large	1361	22.47

Table 3
SOFC micro-CHP central estimate result

Dwelling	EAC (£)	Optimum stack capacity (kWe)	Optimum boiler capacity (kWth)
Small	791	0	11.97
Average	987	0	14.82
Large	1347	1.25	20.58

Given the large number of assumptions in the central estimates, and significant uncertainty in many of them, this single point solution is of limited value. The following sections explore the sensitivity of the solution to variations in key input parameters, and the potential significance for technology development and market penetration.

6.3. Sensitivity to stack capacity

It is of interest to examine how important the optimum stack capacity (i.e. stack capacity that results in minimum equivalent annual cost of meeting energy demand) is in terms of economic benefit to the energy user. If the equivalent annual cost of meeting energy demand across a variety of stack capacities maintains a relatively stable value, one could conclude that manufacturing an optimum capacity stack is relatively unimportant. Alternatively, if the EAC across a variety of stack capacities exhibits a steep gradient then it is more important to determine the optimum stack capacity. Fig. 3 plots EAC of meeting energy demand divided by the corresponding baseline EAC from Section 6.1, against installed SOFC capacity on the *x*-axis, for each of the three energy consumption profiles and central estimate input parameters discussed in Section 5.

Fig. 3 exhibits the typical characteristics of cost versus installed capacity curves. At zero installed CHP capacity, the EAC of meeting energy demand is equal to the baseline cost presented in Section 6.1. As a small amount of CHP capacity is added to the system (i.e. moving a short way right on the *x*-axis), the EAC rapidly increases, consistent with the significant additional cost of having any stack in the system and its associated balance of plant. However, as further CHP capacity is added to the system (i.e. continuing further to the right on the *x*-axis in Fig. 3), the benefits obtained from operating the additional CHP capacity begin to outweigh the additional capital cost, and the EAC decreases. Finally, as

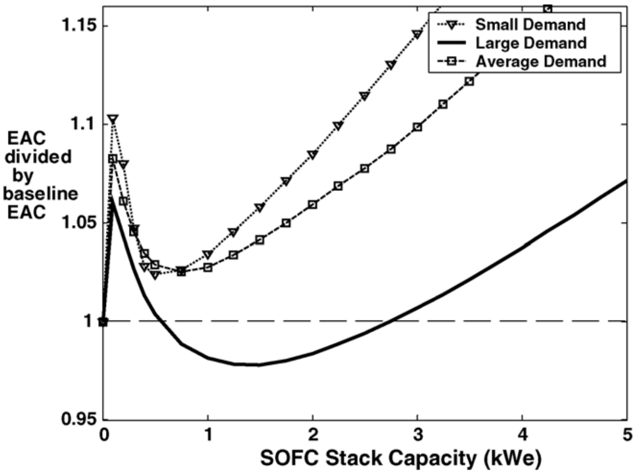

Fig. 3. Equivalent annual cost (EAC) of meeting energy demand divided by corresponding baseline EAC vs. installed SOFC stack capacity for small, average, and large dwellings.

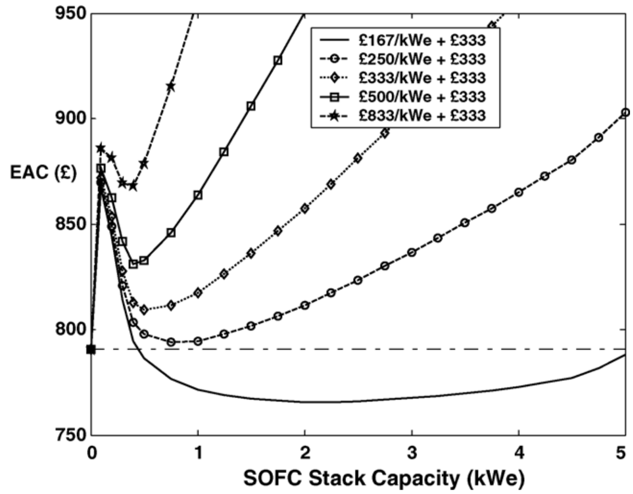

Fig. 4. Equivalent annual cost (EAC) of meeting energy demand in a small dwelling vs. installed SOFC stack capacity—sensitivity over a range of stack capital costs.

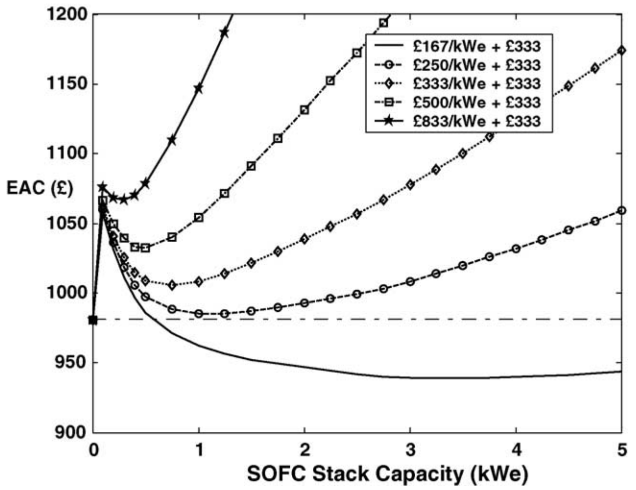

Fig. 5. Equivalent annual cost (EAC) of meeting energy demand in an average dwelling vs. installed SOFC stack capacity—sensitivity over a range of stack capital costs.

more CHP capacity is added to the system, and less electricity and heat demand can be served by that capacity, and EAC of meeting energy demand increases (i.e. extra CHP capacity is installed but there is no load for it to serve, thus increasing the capital cost with no operating cost benefit). These tensions between capital and operating costs result in the “tick” shape of all EAC versus capacity curves in this paper—a sharp initial spike, falling to a minimum, and then rising.

There is an important difference in the shape of the curves in Fig. 3 for the three dwellings analysed. The small dwelling EAC is relatively sensitive to stack capacity (i.e. the “small dwelling” curve is steeper than the other two), whilst the average and large dwellings show relatively less variation in EAC in the 0–5 kWe stack capacity range (i.e. their curves have a shallower gradient than the “small dwelling” curve). This means that it is more important to choose the correct stack capacity for dwellings with smaller energy demand.

Reflecting the result in Section 6.2, the large dwelling is the only case with a minimum EAC below that of the grid/boiler baseline (represented by the horizontal line on the figure). It also offers relatively little variation in EAC between approximately 0.75 and 2.75 kWe stack capacity, implying that a manufacturer could choose a capacity anywhere in this range with little effect upon an investors incentive to purchase the technology. For the small and average dwellings, at the 0.75 kWe level, “next-best” stack capacity (i.e. where EAC is lowest, but micro-CHP stack capacity is above zero) is apparent, although it is noted that this system is still inferior to the grid/boiler baseline result of Section 6.1.

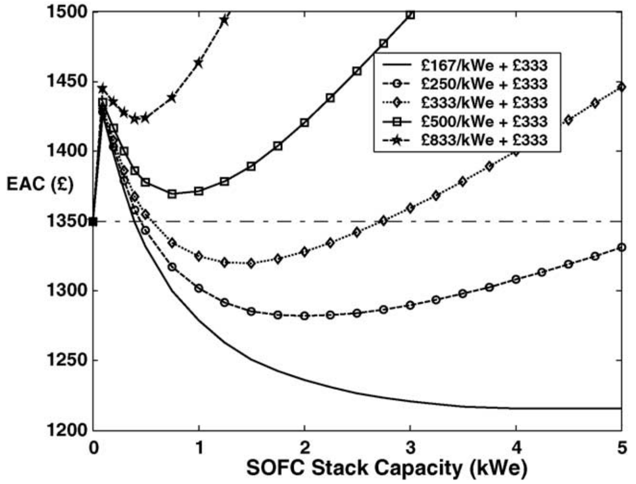

Fig. 6. Equivalent annual cost (EAC) of meeting energy demand in a large dwelling vs. installed SOFC stack capacity—sensitivity over a range of stack capital costs.

6.4. Sensitivity to capital cost

Sensitivity to capital cost is now explored. The estimates of capital costs given in Section 2 (US$300 and above) are used as a guide to obtain Figs. 4–6, which plot equivalent annual cost against stack capacity for each demand profile under a number of “cost per kWe” scenarios. The fixed cost to include any stack in the system is £333 (US$600)[3] which is considered to be a basic system cost, and variable costs (per kWe installed) used are £167 (US$300), £250 (US$450), £333 (US$600), £500 (US$900) and £833 (US$1500). When the £333 fixed cost is incorporated, these estimates are on average slightly higher than those indicated in Section 2 because it is perceived that there is some loss of economies of scale in the 0–5 kWe range we are investigating, resulting in higher prices per kWe in this study.

Figs. 4 and 5 show that both the small and average dwellings should only install a fuel cell once the stack cost drops below £250 kWe^{-1} plus the £333 basic cost, because the £250 kWe^{-1} curves almost touch the horizontal line in the

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[3] Exchange rate used here is UK£1 = US$1.80.

figures which correspond to the grid/boiler baseline of Section 6.1. For the large dwelling, this figure is approximately £400 kWe^{-1} plus the £333 basic cost.

Another important result is the rate at which the optimum stack capacity decreases with respect to increasing capital cost. The optimum stack capacity—where EAC reaches a minimum—for the £167 kWe^{-1} curves (plus £333 basic cost) is at approximately 2, 3, and 5 kWe stack capacity for the small (Fig. 4), average (Fig. 5) and large (Fig. 6) dwellings, respectively. Optimum stack capacity then falls rapidly with increasing stack capital cost in all cases—for the average dwelling to approximately 1 kWe at £250 kWe^{-1} and then zero at £333 kWe^{-1}, implying that relatively small changes in the total capital cost of the stack translate to large changes in optimum stack capacity.

Finally, the lower the capital cost per kWe installed, the less sensitive the EAC is to stack capacity (all curves exhibit a shallower gradient at lower capital cost per kWe). Therefore, if capital costs are low, then precise sizing of the SOFC generator capacity is less important.

6.5. *Sensitivity to SOFC lifetime*

Stack lifetime estimates of Section 2 suggested that lifetimes of 40,000 h with acceptable voltage degradation are currently achievable for large-scale tubular SOFC technology. As the technology under analysis here is embryonic, a range of lifetimes around this value will be investigated. We have chosen 3, 5 and 7 years as the input lifetime values to give an indication of the relevance of this parameter to model outcomes. Industry expectations are for a stack lifetime of 10 years (or boiler-equivalent lifetime), and technology developers are working towards this target. Therefore, the upper limit used here is conservative. The lifetime of the stack does not affect how it is dispatched, but does change the equivalent annual capital cost of the system. Therefore, this section simply observes the effect of changing the annuity factor on the equivalent annual capital cost of the stack (see Figs. 7–9).

In Figs. 7–9 stack lifetime clearly has a significant influence on optimum stack size and on system economics generally, although the influence across the range of lifetimes chosen is less than the influence of capital cost from Section 6.4. In all cases the 3-year lifetime stack is not an attractive investment. For 5-year lifetime the large dwelling optimum stack capacity is 1.25 kWe, but this investor would choose not to invest for small and average dwellings. For 7-year lifetime, the small and average dwellings become an attractive investment with a 0.75 and 1 kWe stack respectively, and optimum stack capacity for the large dwelling increases to nearly 2 kWe.

Note that the EAC curves become steeper as stack lifetime becomes shorter, implying that a shorter-lived stack owner has more to gain from purchase of a system with an accurate optimum stack capacity. Another interesting result here is that the small energy demand profile appears to benefit more from the increase in lifetime than the average profile (the optimum “average” case EAC just equals the grid/boiler baseline result, whilst the “small” case dips well below that line). An explanation for this lies in the specifics of the energy demand profiles—the small energy demand profile may have more coincidence of electricity and heat demand, or a larger portion of the energy demand within the capacity of stack (i.e. a larger percentage of total electricity demand at lower than the 0.75 kWe stack capacity).

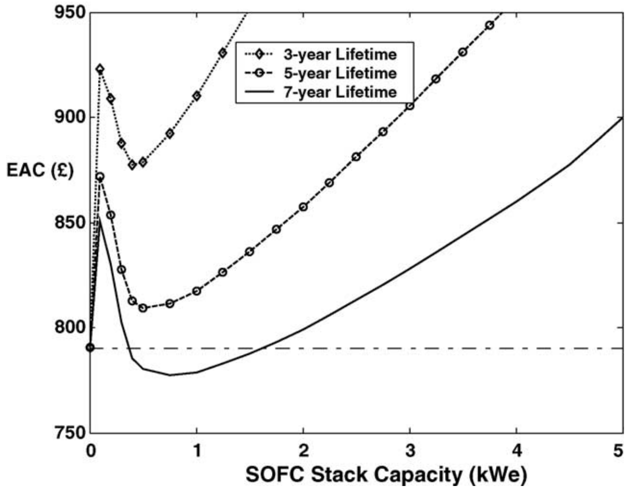

Fig. 7. Equivalent annual cost (EAC) of meeting energy demand in a small dwelling vs. stack capacity—sensitivity over a range of stack lifetimes.

6.6. *Sensitivity to electrical efficiency*

The electrical efficiency used in this simulation ranges from roughly 40% at maximum load up to 54% at minimum load (minimum load in this study is load factor of 0.2). It is possible that a manufacturer would be able to develop a SOFC stack with lower electrical efficiency than this for lower cost,

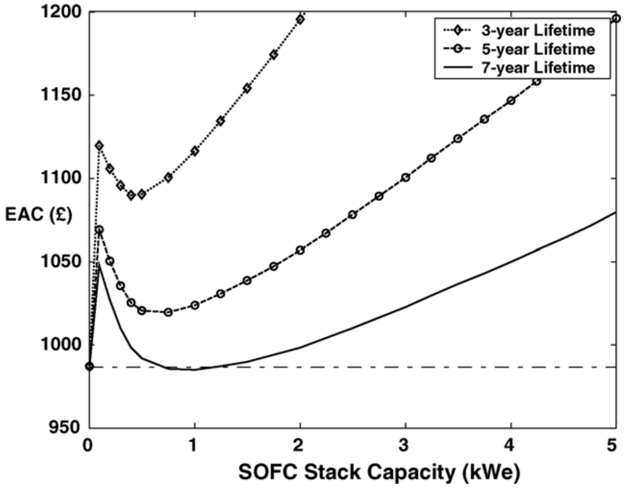

Fig. 8. Equivalent annual cost (EAC) of meeting energy demand in an average dwelling vs. installed SOFC stack capacity—sensitivity over a range of stack lifetimes.

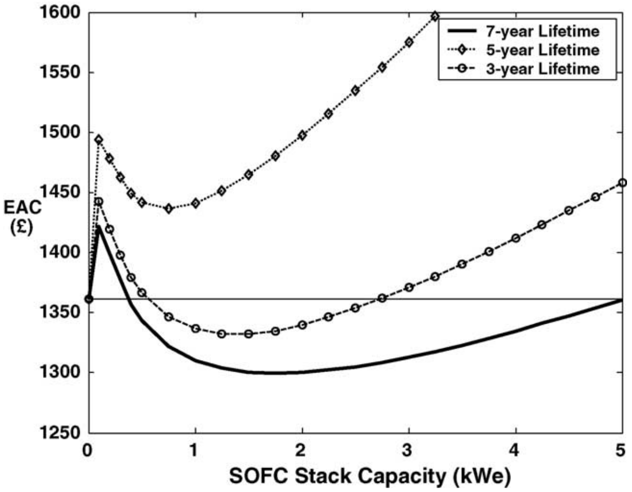

Fig. 9. Equivalent annual cost (EAC) of meeting energy demand in a large dwelling vs. installed SOFC stack capacity—sensitivity over a range of stack lifetimes.

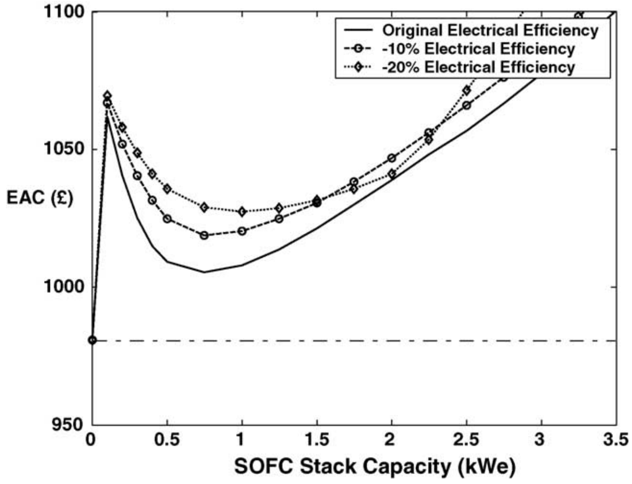

Fig. 11. Equivalent annual cost (EAC) of meeting energy demand in an average dwelling vs. installed SOFC stack capacity—sensitivity over a range of stack electrical efficiencies.

without significant loss in overall efficiency (heat + power) of the micro-CHP system. In order to investigate the benefit obtained by the energy user as a result of lower efficiency we subtract a constant 10 and 20% from the electrical efficiency profile presented in Section 4, whilst maintaining the overall efficiency (heat + power) of the system. The capital cost for these analyses is fixed at £333 basic cost for any stack plus £333 per kWe of installed capacity.

The first point to note about Figs. 10–12 is that the minimum boiler capacity (5 kWth) begins to play an increasing role in the economics of the system. For example, in Fig. 10, for −20% electrical efficiency, the EAC versus capacity curve exhibits a discontinuity at 2 kWe stack capacity where EAC begins to increase more rapidly. This is the point where a trade-off between increased stack capacity and reduced boiler capacity can no longer be achieved because minimum boiler capacity has been reached. This trend is evident to a greater or lesser degree in each of Figs. 10–12.

Another point regarding electrical efficiency is that the most drastically reduced stack electrical efficiency of −20% results in a larger "next-best" stack capacity (i.e. if we ignore the grid/boiler baseline result represented by the horizontal lines in the figures, and take the "next-best" stack capacity based on lowest EAC) in all three cases. From a manufacturers point of view this is interesting because the larger stack may generate higher revenue for the manufacturer from its sale, may be cheaper to manufacture because it is less electrically efficient, but can still provide the customer with close to the best EAC outcome. However, this conclusion would require further analysis, as the "−20%" case is not competitive with the grid/boiler baseline result in any of the dwellings.

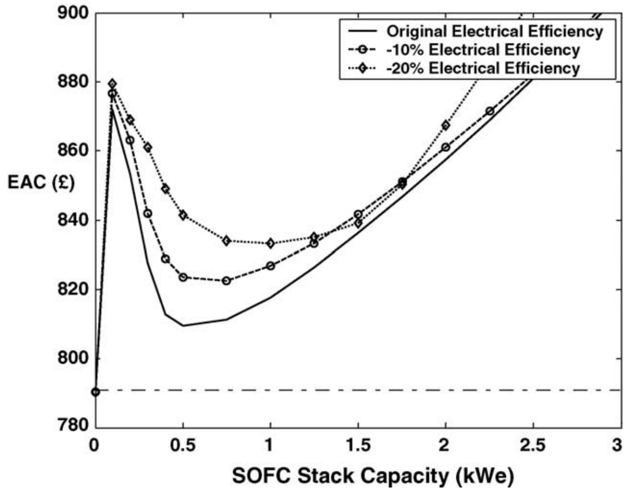

Fig. 10. Equivalent annual cost (EAC) of meeting energy demand in a small dwelling vs. installed SOFC stack capacity—sensitivity over a range of stack electrical efficiencies.

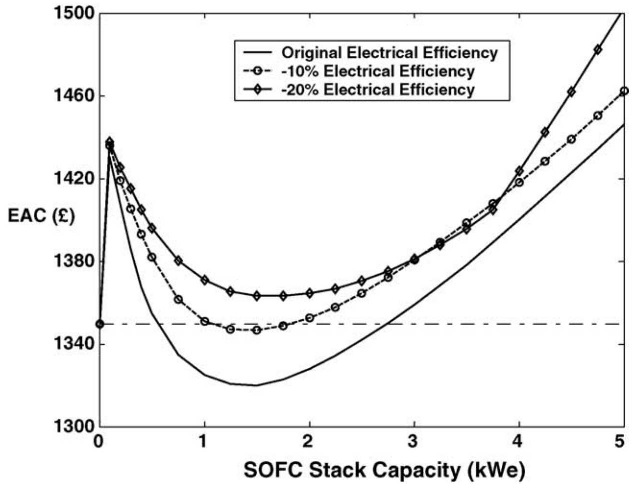

Fig. 12. Equivalent annual cost (EAC) of meeting energy demand in a large dwelling vs. installed SOFC stack capacity—sensitivity over a range of stack electrical efficiencies.

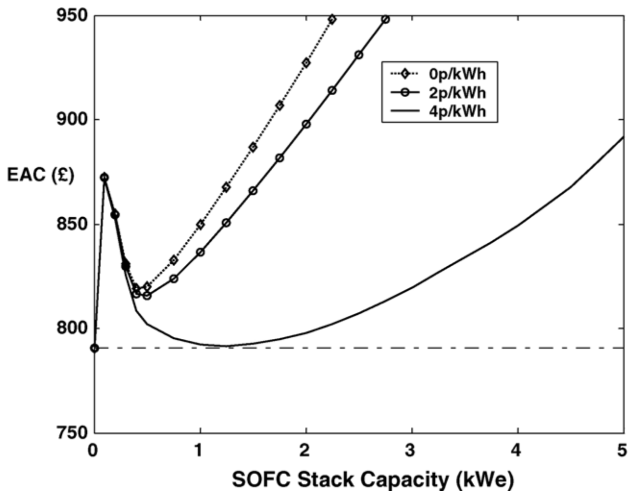

Fig. 13. Equivalent annual cost (EAC) of meeting energy demand in a small dwelling vs. installed SOFC stack capacity—sensitivity over a range of electricity export prices.

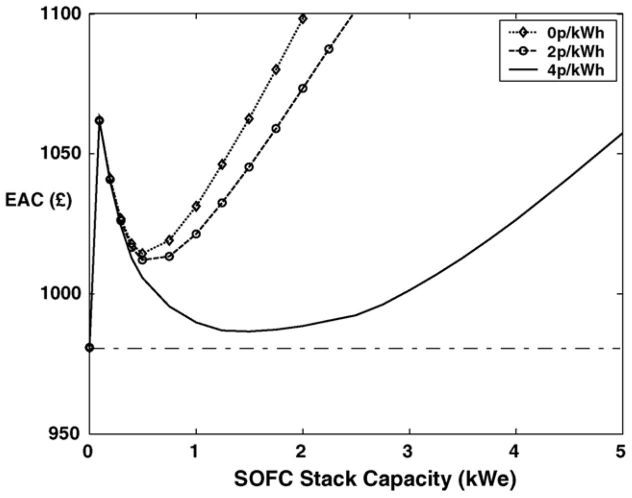

Fig. 14. Equivalent annual cost (EAC) of meeting energy demand in an average dwelling vs. installed SOFC stack capacity—sensitivity over a range of electricity export prices.

6.7. Sensitivity to electricity export prices

The prevailing spark-spread[4] is an important factor when considering investment in CHP. For residential premises that wish to sell electricity generated, the price difference between the sell price and the cost to generate power does not need to be positive for the generator to be dispatched. This is because the cost to meet onsite heat demand may be lower using the CHP unit (and gaining some small revenue from any incidental electricity export) than using the additional boiler, or it may be economically efficient to dump excess heat (limited to 0.5 kWth dump in this study) and gain revenue from the exported power. This tension between natural gas price and electricity export price is important in choosing optimum stack capacity, and is investigated through a sensitivity analysis to electricity export prices. Export prices used are 0, 2, and 4 p kWh^{-1}. All other input variables are identical to the central estimates presented in Section 5 (see Figs. 13–15).

The results in Figs. 13–15 show the importance of revenue from electricity export for stack economics. High electricity export prices, of the order of 4 p kWh^{-1}, indicate much improved EAC, and push the optimum stack capacity to the 1 kWe vicinity for the small and average dwelling cases, and to above 2 kWe for the large dwelling case. On the other hand, low export prices suggest much poorer economics at high stack capacities, and relatively unchanged outcomes at low stack capacities where the system is operating in the base load of the dwelling and therefore electricity export is less important as all electricity is being used onsite.

There is clearly a critical point between 2 and 4 p kWh^{-1} electricity export price where EAC improves significantly and the curve flattens over the range of stack capacities. This is because the revenue gained from export begins to outweigh the increased capital cost of the stack, making it justified to follow a larger portion of the heat load and therefore export more power. However, a number of complex interactions are at work here such as the high part-load efficiency (which can make it economically efficient to generate at low load factors (defined in Section 4), but not at high load factors), tensions between the fuel/electricity import prices and export prices, and the trade-off between the cost of increased stack capacity or increased boiler capacity to meet heat demands.

6.8. Sensitivity to energy import prices

A final sensitivity analysis is carried out to examine the impact of varying energy import prices (fuel and electricity). During the course of this analysis, residential energy tariffs

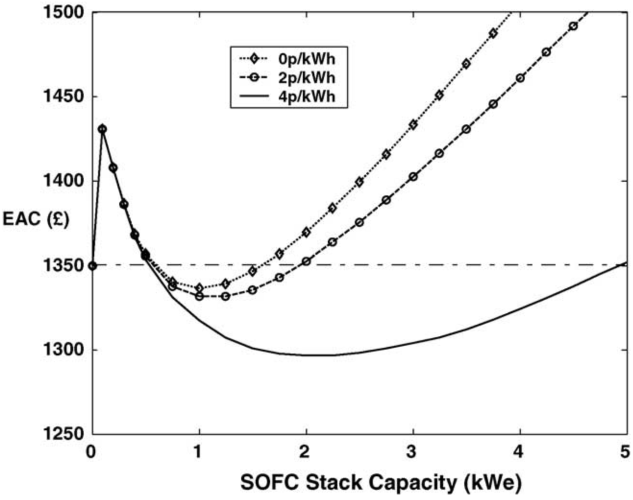

Fig. 15. Equivalent annual cost (EAC) of meeting energy demand in a large dwelling vs. installed SOFC stack capacity—sensitivity over a range of electricity export prices.

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[4] Speak-spread is defined as the difference between fuel and electricity price.

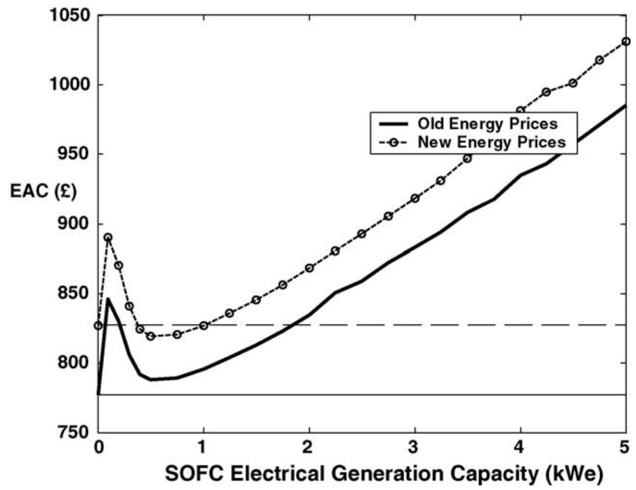

Fig. 16. Equivalent annual cost (EAC) of meeting energy demand in a small dwelling vs. installed SOFC stack capacity for May 2003 (old) energy prices and September 2004 (new) energy prices.

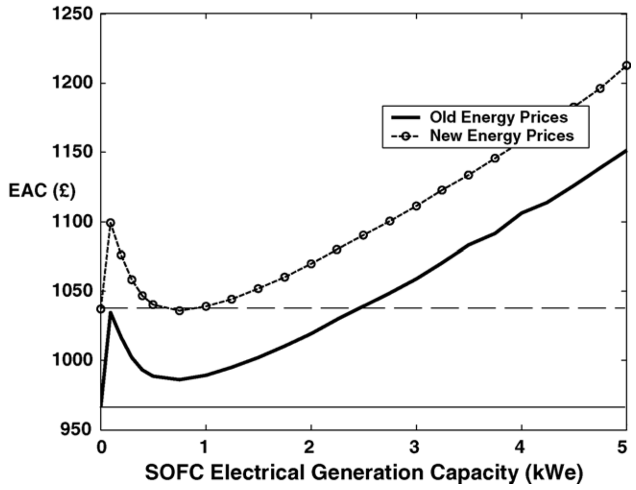

Fig. 17. Equivalent annual cost (EAC) of meeting energy demand in an average dwelling vs. installed SOFC stack capacity for May 2003 (old) and September 2004 (new) energy prices.

changed significantly, with most Suppliers increasing tariffs by of the order of 10–15%. As the central estimate prices used in this analysis were for a London Electricity customer on a general purpose rate in May 2003, we adopt the September 2004 general purpose London Electricity prices for this sensitivity analysis. These new prices are as follows:

- Electricity: 11.94 p kWh^{-1}, for the first 225 kWh per quarter, 7.29 p kWh^{-1} thereafter.
- Gas: 2.499 p kWh^{-1}, for the first 1143 kWh per quarter, 1.572 p kWh^{-1} thereafter.

Figs. 16–18 display the results of this sensitivity analysis.[5]

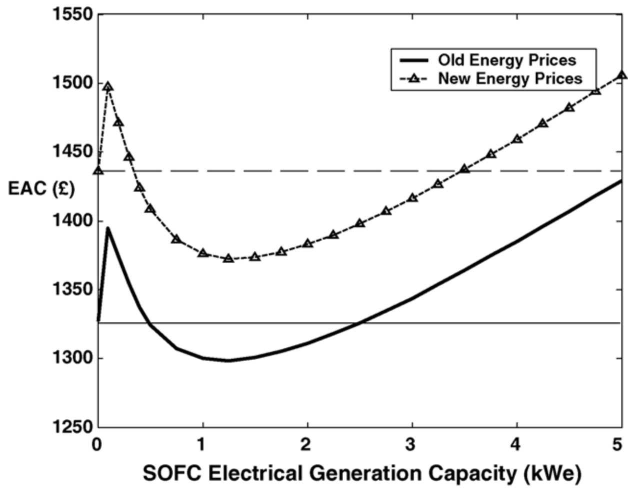

Fig. 18. Equivalent annual cost (EAC) of meeting energy demand in a large dwelling vs. installed SOFC stack capacity for May 2003 (Old) and September 2004 (new) energy prices.

In the small and average dwelling cases, investment in a SOFC-based micro-CHP system has become an attractive investment between "Old" and "New" energy tariffs. In the case of the large dwelling, it has become a more attractive investment than the "Old" energy import price scenario. This is due to the capital costs of the SOFC trading off against increased electricity import price. This amplifies the economic benefit from the SOFC which is now displacing more expensive electricity import, and therefore more capital expenditure is justified to obtain this displacement.

7. Conclusions

We have presented the background situation for decentralised energy in the UK, and a model for investigation of cost-optimum CHP, and applied it to residential micro-CHP solid oxide fuel cell systems. A simple but realistic SOFC system high-level characterisation was presented that allows investigation of the economics of optimum micro-CHP systems with reasonable computational efficiency.

It was shown that the optimum energy delivery system was zero stack capacity (i.e. grid/boiler only system) for small and average UK residential dwellings using central estimates of input parameters. A large dwelling demand profile yielded an optimum stack capacity of 1.25 kWe, indicating that under current conditions this application is likely to be the first target market. However, due to a great deal of uncertainty regarding these parameters, a sensitivity analysis was then performed on key economic drivers. Variation in stack capital cost per kWe, electricity export prices, and energy import prices were found to be the most important of the investigated factors, where small changes in these parameters translated to large changes in optimum stack capacity, equivalent annual cost and the sensitivity of eco-

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[5] Note that small perturbations in these figures are due to a (insignificant) modelling error.

nomic performance to system sizing. A change in capital cost from £333 to £250 kWe^{-1} (plus a basic system capital cost of £333), or a change in electricity export price from 3 to 4 p kWh^{-1}, or a positive movement in energy import prices improved the annual cost for the small and average dwellings to the point where they represent a reasonable investment with a stack capacity of the order of 1 kWe.

The other two sensitivity analyses performed were for stack lifetime and stack electrical efficiency. Stack lifetime is also an important factor, although less so than stack capital cost over the range of investigated values. Increasing the lifetime to 7 years from the 5 year central estimate resulted in all demand cases becoming viable with small stack capacities. This result is intuitive as it relates to the longer period of operation of the equipment, resulting in an increased period over which the initial investment is spread.

The stack electrical efficiency sensitivity analysis illustrated the relative unimportance of extremely electrically efficient technology for residential applications with significant heat demand. Provided the overall efficiency (heat + power) of the system is maintained at high levels, an optimally dispatched system will achieve similar cost savings regardless of electrical efficiency. This accords with the activities of developers already entering the commercial market with residential CHP, where Stirling engines are typically used with electrical efficiencies of only 15–20%.

The results indicate that under current conditions, were SOFC CHP available with the characteristics expected, early markets would certainly exist in larger properties, and also in small and average properties if current energy import prices are maintained. The results highlight that there is a variety of potentially fruitful avenues for expanding this market towards smaller properties, and provides some indications to manufactures and system developers of the relative merits and impacts of each.

8. Further research

As mentioned in this article, forthcoming publications include development of techniques to sample days or generate load profiles that are adequate to provide accuracy in this optimisation approach. More detailed analysis of technical characteristics of a trade-off between current density and stack lifetime in terms of minimum EAC are also the subject of current research.

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