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Effect of operating conditions on performance of domestic heating systems with heat pumps and fuel cell micro-cogeneration

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ABSTRACT

The relative performances of six air source heat pumps (ASHP) and a solid oxide fuel cell micro-combined heat and power (SOFC-mCHP) unit are compared using a modelling approach. The emphasis is in indicating the effect of a wide range of operating conditions and methodologies, rather than detailed analysis of the performance of the units under limited specific circumstances. The effect of control methodologies is the primary focus but other variables such as the climate and the specification of the buildings to which heat is supplied are considered. Several significant findings emerge. Firstly, a reduction in heating demands due to warmer will reduce the impacts of both heating systems. In the case of ASHPs, lower heat demands improve performance. In the case of SOFC-mCHP systems they reduce the need for auxiliary heating. A wide range of performances may be achieved by ASHPs, even supplying heat to the same building; the way in which ASHP units are controlled has the potential to reduce their impacts by more than a third. The greatest savings achieved by the SOFC-mCHP unit occur when it is run continuously at full output, despite the consequent dumping of excess heat. Although the auxiliary heaters used with them inevitably reduce their overall benefit, they are still capable of significant savings. It is currently possible for the units to offset more emissions than they create.

1. Introduction

To achieve ambitious reductions in greenhouse gas emissions, nations with temperate climates will need to decarbonise the way in which domestic space heating is delivered [1]. Air source heat pumps (ASHPs) and solid-oxide fuel cell micro-combined heat and power (SOFC-mCHP) units have been suggested as two technologies with the potential to contribute towards achieving this [2]. Although many studies have investigated the performance of units in detail, this study considers their relative performance under a wider set of configurations and conditions in order to investigate the effect that these factors may have.

Extensive testing of individual units has been conducted (e.g. [3]) but it is important to consider the effect of a wider range of operational conditions. Field trials (e.g. [4–6]) provide valuable data which has been analysed to suggest potential areas for improvement (e.g. [7,8]) but are generally limited in the scope of the options which they can consider. To address this, detailed modelling has been used by several researchers to analyse the potential performance of different low-carbon heating technologies in various configurations. These studies typically provide an overview of the relative merits of the technologies. Some focus in detail on the performance of a single technology in a specific context and compare this to the default alternative (e.g. [9]) whilst others compare the performance of different technology options (e.g. [10–14]). Consideration is usually given to the effect of the source of central electricity generation and the specification of the buildings to which heat is supplied. However, whilst different control configurations and climates were used in the studies, indicating that they have an effect, these effects have not yet been explored fully. Although the optimum control of individual units has received attention (e.g. [15]), studies which investigate the effect of the control and configuration of the units in the context of the overall systems in which they operate are surprisingly few. Madani et al. [16] showed the potential for different control techniques to improve heat pump performance but focussed solely upon techniques that take flow temperatures as inputs.

The approach taken in this study was to simulate the relative performance of heating system (i.e. the units and their auxiliary systems) operating under a wide range of operational conditions

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Abbreviations: ASHP, air source heat pump; COP, coefficient of performance; mCHP, micro combined heat and power; SOFC, solid oxide fuel cell.

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rather than to focus on detailed simulation of the impacts of the units under specific conditions. The parameters which were identified as being of interest were the control methodologies used by the heating systems and the climate in which they operate. Different building specifications were additionally simulated, providing a consistent comparison across these parameters. In addition to characterising the effect of these parameters, the potential of appropriate control systems to achieve significant reductions in energy demand and emissions was demonstrated.

2. Method

2.1. Overview of conditions investigated

The effect of a wide range of operating conditions on the performance of the units was investigated by modelling the systems and then simulating them under 267 permutations representing the scenarios and operational parameters detailed below. Performance was considered in terms of efficiency and greenhouse gas emissions (see Section 2.2). The performance of six ASHPs, a SOFC-mCHP unit and a condensing gas boiler were compared (see Section 2.3). The permutations were arranged in groups:

- One hundred and forty-seven permutations were formed from six models of air source heat pumps and a condensing gas boiler in three building specifications with seven combinations of control methodology and buffer tank capacity. These options are described in Section 2.4.
- Seventy-two permutations were formed by simulating a SOFC-mCHP unit with different control methodologies and configurations. The first 36 consisted of six buffer sizes and six control methodologies. An additional 36 permutations were formed from two variations on the highest performing methodology analysed earlier with three building specifications and six buffer tank sizes. These are described in Section 2.5.
- Finally, 48 permutations considered the potential effect of climate change on the performance of the units. Simulations of two ASHPs, the SOFC-mCHP unit and a condensing gas boiler were conducted using data for 12 climates. The selected climate data is described in Section 2.6.

The three building specifications were constructed to be representative of a semi-detached house, a semi-detached house with enhanced heat emitters (effectively an underfloor system) and the same house with enhanced heat emitters and reduced heat losses. These are described in Section 2.7.

2.2. Performance metrics

Results are based upon the total annual energy flows. Efficiency calculations for the SOFC-mCHP unit used the gross calorific value of fuel input and their alternating current electrical output (i.e. net of inverter losses). ASHP performance is expressed as a coefficient of performance (COP, i.e. the quotient of heat delivered by an ASHP to electrical work required). *Unit* performance metrics were based upon energy flows to and from the individual units. *System* performance metrics were based upon the heat flows to the hot water tank and heat emitter system and the fuel and net electrical inputs to both the units and their auxiliary systems (i.e. including auxiliary heaters and pumps).

Greenhouse gas emissions were also used to assess system performance. An emissions factor of 189 g-CO_2e/(kW h) was used for natural gas, based upon its content and transmission efficiencies [17]. Emissions upstream of entry to the national transmission system were not included. An electrical grid carbon emissions factor of 586 g-CO_2e/(kW h) was used based upon fixed emissions characteristics for each generation type [18,19] with the mix of generation weighted by heat demand using time-series generation data [20].

It should be noted that operational emissions were used; if the aim of a study were to provide a full comparison between micro-generation systems it would be necessary to complete a full life-cycle assessment of their impacts [21,22]. Results comparing the emissions associated with ASHPs and mCHP units are very sensitive to the carbon emissions factors which are assumed but this is explored in detail elsewhere and is not pursued further in this study [10–14,23].

Table 1
Nominal ASHP performances.

Unit	COP	Reference
ASHP A	4.2	[25]
ASHP B	3.0	[26]
ASHP C	3.6	[27]
ASHP D	3.5	[27]
ASHP E	3.4	[25]
ASHP F	4.4	[25]

2.3. Heating system performance

The nominal COPs of the ASHPs are given in Table 1. These figures relate to standardised test conditions [24] but the sources referred to include performance data at between 8 and 12 additional sets of conditions for each unit.

An interpolation method was used to determine the performance of the ASHP units. The exergy efficiency of each unit was calculated at each of the standardised test conditions for which data was available [25–27]. The weighted average of the exergy efficiencies at the four test conditions with source and sink temperatures bounding the temperatures in the model was calculated during each time step. This exergy efficiency was then used to calculate the power consumption under those conditions. Some studies [13,28] have successfully applied parametric relationships between the performance of ASHP units and the temperatures they operate between. The method used here takes advantage of the observation that the exergy efficiency of heat pumps tends to be approximately constant between test conditions [29] in order to improve confidence in the model when the simulated conditions tended towards the more extreme test conditions. The heat which was generated by each heating unit was also constrained by its maximum and minimum heat generation capacity.

The efficiencies of the SOFC-mCHP unit are given in Table 2 for two electrical output levels. Because of the low heat generation capacity of the SOFC-mCHP unit and its slow ramp-rate, its operation was supplemented by an auxiliary gas boiler. The heat from both units fed into a buffer tank.

The steady-state electrical and thermal efficiencies of the SOFC-mCHP unit were calculated as a function of the output level by linear interpolation from a set of published performance data [30]. A default maximum ramp-rate of 0.06 W/s was assumed based upon known warm-up and cool-down times. The results demonstrate relatively low sensitivity to this assumption (see Section 3.2).

The gas boiler system was modelled with a fixed thermal efficiency of 90%. In reality, the efficiency achieved by such devices is a function of the flow temperature they operate with (and the

Table 2
Steady-state unit efficiencies of SOFC-mCHP unit [30].

	Electrical (net) (%)	Thermal (%)
Peak electrical efficiency (1.5 kWe)	54	21
Peak electrical generation (2.0 kWe)	51	29