# Micro-CHP Accelerator

Final report – March 2011

# Contents

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# Executive summary

By producing both useful heat and electricity locally, combined heat and power (CHP) systems can potentially achieve lower overall carbon emissions than conventional heating systems and grid electricity.

The Carbon Trust's Micro-CHP Accelerator carried out a wide range of activities to better understand the potential benefits of different micro-CHP technologies and the barriers to their adoption.

The project involved a major field trial of micro-CHP units in both domestic and small commercial applications, and a corresponding trial of A-rated condensing boilers to provide a baseline for comparison.

This report provides a concise synthesis and analysis of the results of the field trial, including annual performance data for the first time. It follows two previous updates and in particular should be read in conjunction with the Interim Report published in 2007[1], which contains more detail on the featured technologies, the field trial methodology and discussion of the practical challenges to widespread adoption of micro-CHP in domestic and small commercial applications.

The Micro-CHP Accelerator set out to meet three main objectives.

## Objective 1

### To install a range of micro-CHP units in real operating environments representative of likely UK installations and obtain robust, independently monitored performance data.

The project was the first large-scale, independent field trial of micro-CHP systems in domestic and small commercial applications in the UK.

A total of 87 micro-CHP systems – including 72 domestic Stirling engines and 15 internal-combustion (IC) engine systems – were installed and monitored in typical UK households and small commercial applications. A complementary field trial of 36 condensing boilers provided a baseline for comparison.

The domestic sites were broadly representative of the UK housing stock, including a wide range of different house sizes, ages and types. The commercial sites were typical of existing installations of micro-CHP in the sector, including care homes and community heating.

Key parameters were sampled every five minutes with the aim of capturing a full 12 months of continuous operation to take account of seasonal variation in performance. By the end of the trial, more than 380 million data items had been captured and processed, covering about 44,000 days of operation.

[1] Micro-CHP Accelerator – Interim Report, CTC726, November 2007.

## Objective 2

### To assess the carbon performance of the micro-CHP units relative to alternative heating technologies, in particular condensing boilers.

Prior to the Carbon Trust's Micro-CHP Accelerator, a key barrier to the market introduction of micro-CHP in the UK was a lack of independent data on the performance of units in real applications, including the potential of the technology to make a material and cost-effective contribution to reducing carbon emissions.

To address this need, estimates have been made for the reduction in carbon emissions which can be achieved by substituting micro-CHP systems for A-rated condensing boilers. The estimates were formed using statistical analysis of the field trial results for the two types of heating system. The results show that the savings can be significant when micro-CHP is installed in appropriate applications.

Overall, the domestic Stirling engine micro-CHP systems in the field trial achieved a carbon saving of around 5%, although the performance in individual households varied considerably, such that the likely range of savings was between -4% and +12%.

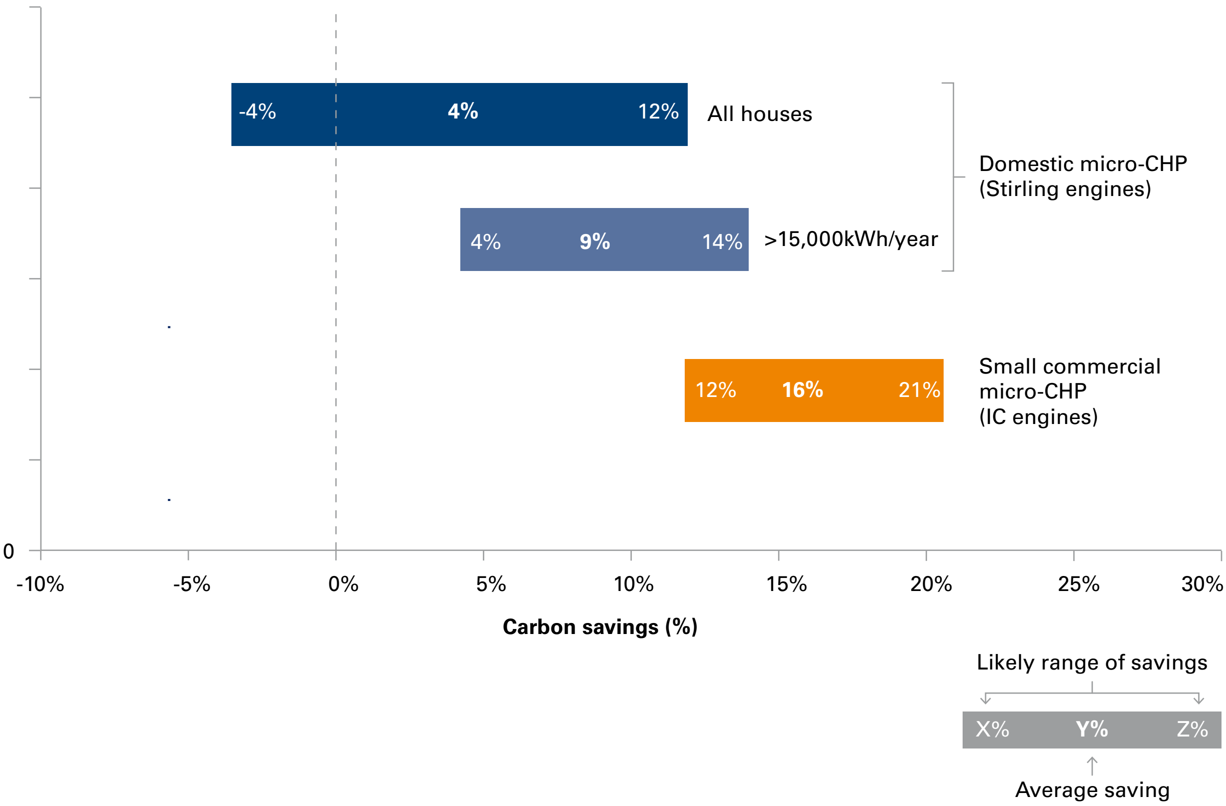
The Stirling engine micro-CHP systems performed better in households with higher heat demands (typically larger detached homes with four or more bedrooms). For those households with heat demands of more than 15,000kWh a year the overall saving was around 9%, equivalent to around 400kg per year for a 'typical' large house. This should therefore be the target market for these micro-CHP systems.

The performance of individual domestic micro-CHP systems is also determined by the ratio of heat to power generated, overall efficiency, user settings and behaviour, controls, and the efficiency of pumps and ancillary components.

The field trial also showed that significant savings could be achieved by installing micro-CHP systems in small commercial applications.

Deployed as the lead boiler in a typical small commercial plant room, the IC-engine micro-CHP systems in the field trial would typically achieve overall carbon savings of around 16%, equivalent to an absolute annual carbon saving of around 15t$CO_2$.

***Figure E1*** *Summary of percentage annual savings for individual sites in the field trial*



## Objective 3

### To provide general insights to inform future technology development and policy decisions relating to micro-CHP

The Micro-CHP Accelerator has identified the key drivers of the performance of micro-CHP systems, which should inform the development of the technology and provide an evidence base to help make policy decisions around the technology. Key priorities include reducing installed cost, targeting appropriate applications, increasing electrical efficiency and optimising installation and controls.

#### Reducing installed cost

At market introduction, the marginal cost of a Stirling engine micro-CHP system over an equivalent condensing boiler is expected to be around £2,500. At this price, the value of the electricity generated by the micro-CHP systems in the field trial is insufficient on its own to provide an attractive payback for the majority of consumers. Even taking account of the incentives available under the new system of Feed-in Tariffs (FITs), the payback is around 16 years for a typical larger household with an annual heat demand of 20,000kWh. For small commercial micro-CHP, for which no such incentives are currently available, the payback period is estimated to be 20-25 years.

A key challenge is therefore to reduce the installed cost of micro-CHP systems through economies of scale and optimised design and manufacturing to provide an attractive payback for consumers.

#### Targeting appropriate applications

The economics of domestic micro-CHP are much more attractive in larger houses as, while the initial installed cost is the same, the absolute carbon and cash savings are roughly proportional to the annual heating bill. The field trial has also shown that the efficiency of micro-CHP systems is typically better in these households. The estimated payback varies dramatically between the lowest and highest annual heat demands observed for houses in the field trial – in the largest houses the micro-CHP system provides a payback within around 10 years. For smaller houses the payback period could be longer than the typical life of a heating system at over 30 years.

Micro-CHP installers should therefore take care to evaluate the suitability of target houses by estimating the annual heat demand on a case-by-case basis. Larger detached houses with more than three bedrooms are likely to be an attractive initial market.

The small commercial micro-CHP systems in the field trial consistently achieved significant carbon savings. Although the estimated payback periods are relatively long, small commercial applications with high and consistent demands for heat, such as care homes and leisure centres, may also be attractive initial markets for micro-CHP technology.

Any policy framework put in place for this technology should also ensure that financial incentives for micro-CHP and other low carbon heating technologies encourage installations only at appropriate sites. The Microgeneration Certification Scheme's product and installation standards provide a good basis for this.

#### Increasing electrical efficiency

The economics of micro-CHP systems can be improved further by increasing the amount of electricity generated for a given amount of gas burned, as electricity has a higher value than heat. For example, a realistic increase in the electrical efficiency of a typical Stirling engine micro-CHP system from 6% to 9% would roughly halve the payback period[2].

#### Optimising installation and control

Although the importance of different factors is complex and still poorly understood, the carbon saving achieved by installing domestic micro-CHP systems could potentially be significantly improved by optimising their installation and operation. In particular, the field trial has demonstrated the importance of ensuring that micro-CHP systems have long operating cycles to minimise the impact of electricity consumed during start-up and shut-down.

[2] Note that this range may be conservative. We understand that higher electrical efficiencies have been achieved in laboratory test conditions for a Stirling engine micro-CHP system now available commercially in the UK.

## Market potential

If the costs of micro-CHP systems can be reduced with economies of scale to make them sufficiently attractive to consumers, the potential benefits could be substantial.

In the domestic sector, there are up to 8 million houses in the UK with a high enough annual heat demand to ensure that micro-CHP systems would achieve a significant carbon saving over A-rated condensing boilers. If this entire market could be addressed, up to about 4 million tonnes of $CO_2$ could be saved each year.

There is also a significant potential market for micro-CHP in non-domestic buildings. The most attractive sectors are likely to be those in which the heat demand per building is typically high and consistent, such as nursing and care homes and leisure centres. These sectors are also likely to be particularly attractive as they include a high proportion of buildings that are owned and occupied by local authorities. The potential carbon saving in these two sectors alone is estimated to be greater than 100,000t$CO_2$/year in around 20,000 buildings.

However, there may be a limited window of opportunity during which to realise this potential.

As the carbon intensity of grid electricity is expected to be reduced in the UK over the next 20 years, the benefits of micro-CHP relative to alternative heating systems will also fall. A range of realistic scenarios suggest that the window of opportunity for Stirling engines may be as short as five to 10 years, or up to 15 to 20 years if deployment of low carbon generating capacity proceeds more slowly than anticipated. Stakeholders should also consider other major economies which are more dependent on fossil fuels for electricity generation (and which are likely to remain so for some time) as potential markets for micro-CHP.

The Carbon Trust's Micro-CHP Accelerator has demonstrated that this technology can achieve significant carbon savings against alternative heating systems in both domestic and non-domestic buildings, particularly when the demand for heat is high and consistent.

But a number of challenges remain, including reducing costs, increasing efficiency and optimising installation and controls.

# 1. Introduction

By producing both useful heat and electricity locally, combined heat and power (CHP) systems can potentially achieve lower overall carbon emissions than conventional heating systems and grid electricity. In recent years a number of micro-CHP systems with electrical outputs of less than 50kW have been developed for domestic and small commercial applications.

Between 2005 and 2008 the Carbon Trust's Micro-CHP Accelerator carried out the first large-scale, independent field trial of micro-CHP systems in domestic and small commercial applications in the UK, together with a complementary field trial of condensing boilers.

The objectives of the Micro-CHP Accelerator were to:

### 1. Install a range of Micro-CHP units in real operating environments representative of the likely UK installations; and to obtain robust, independently monitored performance data

Section 3 of this report presents the core results of the field trial for micro-CHP and condensing boilers

### 2. Assess the carbon performance of the Micro-CHP units relative to alternative heating technologies, in particular condensing boilers

Section 4 analyses their relative carbon performance based on the results of the field trial

### 3. Provide general insights to inform future technology development and policy decisions relating to Micro-CHP

Sections 5-7 explore the importance of the carbon intensity of grid electricity, the economics of micro-CHP and the potential market

This report provides a concise synthesis and analysis of the results of the field trial, including annual performance data for the first time. It follows two previous updates and should be read in conjunction with the Interim Report published in 2007, which contains more detail on the featured technologies, the field trial methodology and discussion of the practical challenges to widespread adoption of micro-CHP in domestic and small commercial applications.

The complete set of results for individual field trial sites will be published as a database to accompany this report.

# 2. Background to the field trial

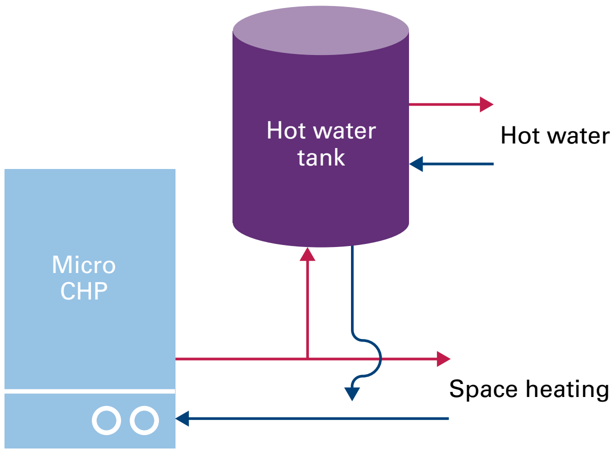
## Domestic micro-CHP

The domestic micro-CHP systems monitored in the field trial were all based on the external combustion Stirling engine[3]. Typical Stirling engine domestic micro-CHP systems have peak thermal outputs in the range of 8-15kW and peak electrical outputs in the range of 1-3kW.

Domestic micro-CHP systems were installed as the main heating system, providing both space heating and domestic hot water to a single household. Systems were sized to meet the heating needs of the households. *Figure 2.1* shows a schematic of the basic domestic micro-CHP configuration, which includes a hot water tank in all cases.

A total of 72 domestic micro-CHP installations were monitored in the field trial, including the systems listed in *Figure 2.2*. Note that some of these devices have been superseded by later models introduced since the field trial. The majority of the units monitored were Whispergen Mk4 and Mk5.

***Figure 2.1*** *Schematic of domestic micro-CHP installations*




[3] Other micro-CHP technologies, including those based on fuel cells, were not included in the field trial as they were not commercially available at the time the trial was commissioned.

***Figure 2.2*** *Domestic micro-CHP models featured in the field trial*

| Manufacturer | Model | Technology | Market Status at time of trial |
|---|---|---|---|
| Whispergen | Mk4 | Stirling engine | No longer made |
| Whispergen | Mk5 | Stirling engine | Early market |
| Microgen[4] | Microgen | Stirling engine | In development |
| Disenco[5] | Home Power Plant | Stirling engine | In development |
| Baxi Innotech | Home Heat Centre | PEM fuel cell | Prototype |

By the end of the trial, a total of 1,015 valid months of domestic operation had been collected, including 57 sites for which 12 or more continuous months of valid data were available.

There were a wide range of different house types in the domestic trial; these were broadly representative of the UK housing stock.

## Small commercial micro-CHP

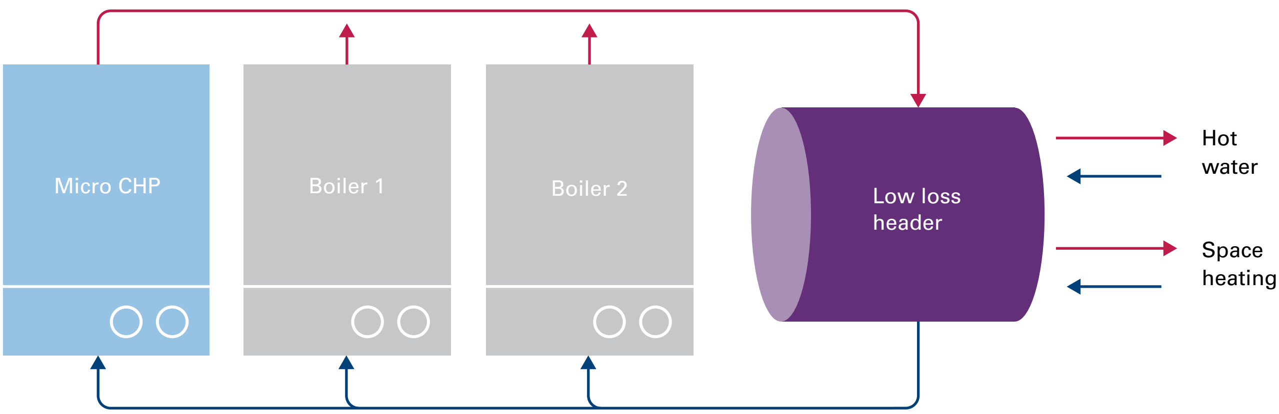
In a small commercial plant installation, the micro-CHP unit is designed to act as lead boiler in the plant room for a small commercial environment, alongside conventional boilers. Typical IC engine commercial systems have peak thermal outputs in the range of 12-25kW and peak electrical output in the range of 5-10kW.

As illustrated in *Figure 2.2*, the small commercial micro-CHP systems in the field trial were typically installed as the lead boiler in the plant room of care homes, residential and community heating schemes.

As is common practice for commercial applications, the systems were designed to achieve long running hours (>6,000 hours/year) and sized to match the electrical output of the micro-CHP system to the electrical baseload of the site to minimise the proportion of the electricity generated that was exported.

A total of 15 small commercial micro-CHP installations were monitored, including five different models from four manufacturers, as listed in *Figure 2.4*. The majority were Baxi Dachs devices. In total, 196 months of valid operational data were collected. Again, note that some of the systems have been superseded since the trial was completed.

***Figure 2.3*** *Schematic of small commercial micro-CHP installation*




[4] In February 2007 BG group announced the closure of Microgen. In August 2007 the formation of Microgen Engine Corporation was announced, in partnership with Stirling engine developer Sunpower and various European boiler manufacturers. This new company has continued to develop the original Microgen technology and is a supplier to various boiler manufacturers.

[5] In February 2010 Disenco Ltd was placed into administration. The business and assets of Disenco were purchased out of administration by Somemore Ltd, which has granted an exclusive license to a new company, Inspirit Energy Ltd, to use the intellectual property to continue the development and commercialisation of the Disenco micro-CHP unit.

***Figure 2.4** Small commercial micro-CHP models featured in the field trial*

| Manufacturer | Model | Technology | Market status at time of trial |
|---|---|---|---|
| Baxi | Dachs | IC engine (natural gas) | Mature |
| Baxi | Dachs | IC engine (oil) | Mature |
| EC Power | XRGI 13 | IC engine | Early market |
| Frichs | Frichs 22 | IC engine | Mature |
| Fiat | Totem | IC engine | No longer made |

## Domestic condensing boilers

As part of this project the Carbon Trust also conducted a field trial of condensing boilers in domestic applications to provide a robust baseline against which to compare the performance of micro-CHP systems. The Energy Saving Trust has also conducted a field trial of domestic boilers using the same methodology. Data from the two trials have been combined and presented together in this report.

As illustrated in *Figure 2.5*, all of the condensing boilers included in the field trial were 'system' boilers installed in domestic heating systems including a hot water storage tank.

In total, 36 condensing boilers were monitored, including 24 different models as shown in *Figure 2.6*.

***Figure 2.5** Schematic of a domestic (system) boiler installation*

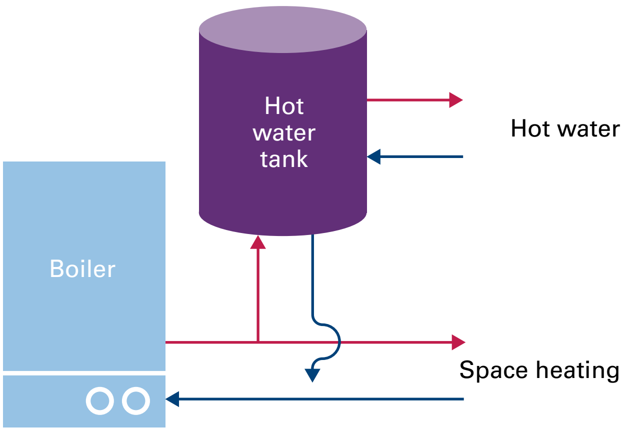


***Figure 2.6** Condensing boiler models featured in the field trial*

| Make | Model | Seasonal efficiency | SEDBUK rating |
|---|---|---|---|
| Baxi | Barcelona | 90.7% | A |
| British Gas | 330 | 90.8% | A |
| Gledhill | AGB5025 | 90.4% | A |
| Halstead | Eden SBX30 | 90.4% | A |
| Ideal | Classic HE18 | 87.5% | B |
| | Icos HE24 | 90.2% | A |
| | Icos M3080 | 90.2% | A |
| | Icos HE15 | 90.4% | A |
| | Icos M3080 | 90.2% | A |
| Potterton | Promax 24HE Plus | 91.2% | A |
| Vaillant | Ecomax 618/2E | 91.2% | A |
| | Ecomax Pro 18E | 90.6% | A |
| | Ecomax Pro 28e | 90.6% | A |
| | ECOTEC PLUS 618 | 91.2% | A |
| | ECOTEC PLUS 624 | 91.2% | A |
| | ECOTEC PLUS 630 | 91.2% | A |
| Worcester | Greenstar 12Ri | 90.1% | A |
| | Greenstar 15Ri | 90.1% | A |
| | Greenstar 18Ri | 90.1% | A |
| | Greenstar 24i | 90.2% | A |
| | Greenstar HE ZB7-27 | 90.7% | A |
| | Greenstar R28 | 90.7% | A |
| Yorkpark | Microstar MZ22C[6] | Not known | Not known |

[6] The Microstar MZ22C boiler is not listed on the SEDBUK database so the efficiency is not known in detail. However, it is a similar model to an existing B-rated boiler.

By the end of the trial, a full year's continuous operation was available for 34 of the sites, and a total of 400 valid months of operation had been collected.

## Field trial methodology

The micro-CHP units in the field trial were installed by device manufacturers under contract to the Carbon Trust to monitor the performance of the systems and provide data to a carefully defined specification. Field trial sites were chosen by the participating manufacturers and consortia.

Key parameters were sampled every five minutes with the aim of capturing a full 12 months of continuous operation to take account of seasonal variation in performance. By the end of the trial, more than 380 million data items had been captured and processed, covering about 44,000 days of operation.

The Carbon Trust's team validated the quality of the data by checking the energy balance of the systems, and carried out substitution for missing data points according to a defined set of rules. For more details see the Interim Report.

## Technology development

The Stirling engine and IC-engine micro-CHP systems monitored as part of the Micro-CHP Accelerator were models that were available in the UK during the period of the field trial between 2005 and 2008. It is to be expected that the technology has since improved. Indeed, a later iteration of the Stirling engine units in the trial has since been released, and the performance is believed to have been improved by implementing lessons learned in the trial itself.

In future, fuel cell-based micro-CHP systems may offer significantly greater carbon savings in both domestic and small commercial applications due to their potential to operate with much higher electrical efficiencies than systems based on heat engines. Although none were available to take part in the Micro-CHP Accelerator, a number of systems based on solid-oxide and PEM fuel cells are now in early field trials. However, they are believed to be a few years away from market-ready products.

The results presented in this report should therefore be taken only as indicative of the likely performance of early micro-CHP systems in real applications in the UK. As existing models are optimised and new technologies are introduced, improved performance can be expected.

# 3. Core field trial results

## Performance metrics

To be consistent with the interim reports on the Micro-CHP Accelerator, three key performance metrics are used in this section: thermal efficiency, electrical efficiency (for micro-CHP only) and the carbon benefits ratio (CBR). The metrics are discussed in more detail in the Interim Report, but definitions are given below for reference.

Note that gross calorific values of gas are used throughout this report. Care should be taken when comparing efficiencies quoted here with values calculated using net calorific value, as is common practice in a number of other European countries.

### Thermal efficiency

$$n_{th} = \frac{\textit{Heat Output}}{\textit{Gas Used}}$$

**Where:**

*Heat Output* = space heating provided (kWh) + water heating provided (kWh)

*Gas Used* = gas used by the heating system (kWh)

### Electrical efficiency

$$n_{elec} = \frac{\textit{(Electricity Generated - Electricity Used)}}{\textit{Gas Used}}$$

**Where:**

*Electricty Generated* = gross electricity generated by the system (kWh)

*Electricity Used* = electricity used by the system (controller, pump, etc.) (kWh)

Carbon benefits ratio is a relative metric that enables the relative carbon emissions associated with different heating technologies to be compared; a higher value means lower carbon emissions.

### Carbon benefits ratio

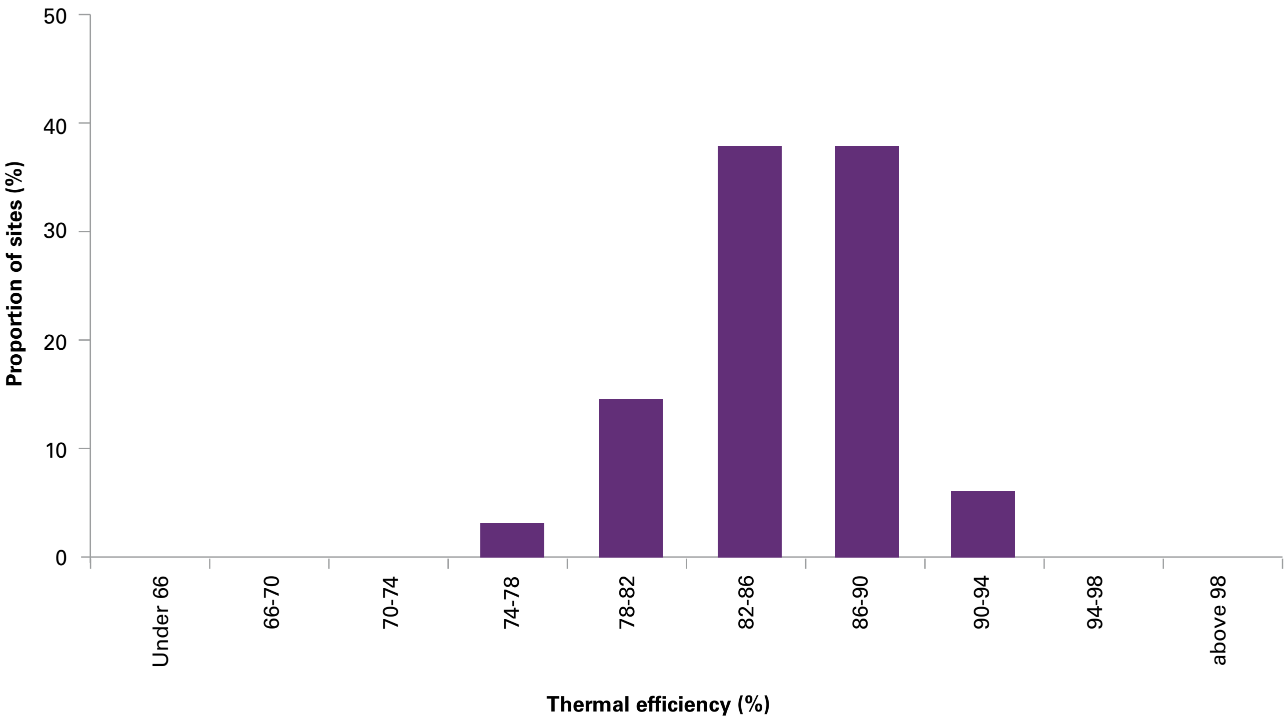
$$n_{elec} = \frac{\textit{(Heat Output x } CEF_{gas} \textit{ - Electricity Generated x } CEF_{elec}\textit{)}}{\textit{(Gas Used x } CEF_{gas} \textit{ + Electricity Used x } CEF_{elec}\textit{)}}$$

**Where:**

$CEF_{gas}$ = carbon emissions factor for gas ($kgCO_2$/kWh)

$CEF_{elec}$ = carbon emissions factor for electricity ($kgCO_2$/kWh)

*Figure 3.1 Condensing boiler thermal efficiency distribution (annual data)*




## Condensing boilers

All but two of the condensing boiler models in the field trial were SEDBUK A-rated systems with quoted seasonal efficiencies of over 90%. *Figure 3.1* shows the distribution of measured annual thermal efficiencies for the condensing boilers in the Carbon Trust and EST field trials. Although a few of the systems did achieve a measured efficiency of greater than 90%, the mean measured annual efficiency was only 85% in the field trial, which is equivalent to the upper end of Band C on the SEDBUK scale. Of the sample 18% achieved measured annual efficiencies of less than 82%, which is equivalent to Band D or worse.

These findings suggest that the current installations of condensing boilers in UK homes may often only be achieving efficiencies around 5% below their SEDBUK declared values.

It appears that condensing boiler systems in the UK are typically designed and set up to operate with return temperatures which are not low enough for efficient condensing operation over long periods. A condensing boiler will only operate in condensing mode with a water return temperature of 57ºC or below and needs this to fall nearer to 50ºC for significant condensation. In modern systems the use of boiler bypass circuits, thermostatic radiator values (TRVs) and oversizing of boilers all tend to increase return temperatures and reduce the likelihood of efficient condensing operation.

The condensing boilers in the field trial were generally existing units already in homes rather than units specifically installed for the trial. On inspection a significant number of them were found to be substantially over-sized for the properties in which they were fitted and this is believed to be common practice in the UK. For example, the average peak heat load of UK houses is around 6kW, but the size ratings of new boilers typically range from 10kW to 30kW.

These factors are expected to reduce the efficiency of condensing boilers, but addressing them represents an opportunity to substantially improve the actual performance of condensing boilers in the UK. This work has been taken forward by the Energy Savings Trust, reflecting their focus on helping to deploy the best commercially available technology in the domestic market[7].

[7] www.energysavingtrust.org.uk

*Figure 3.2* *Condensing boiler CBR distribution (annual data)*

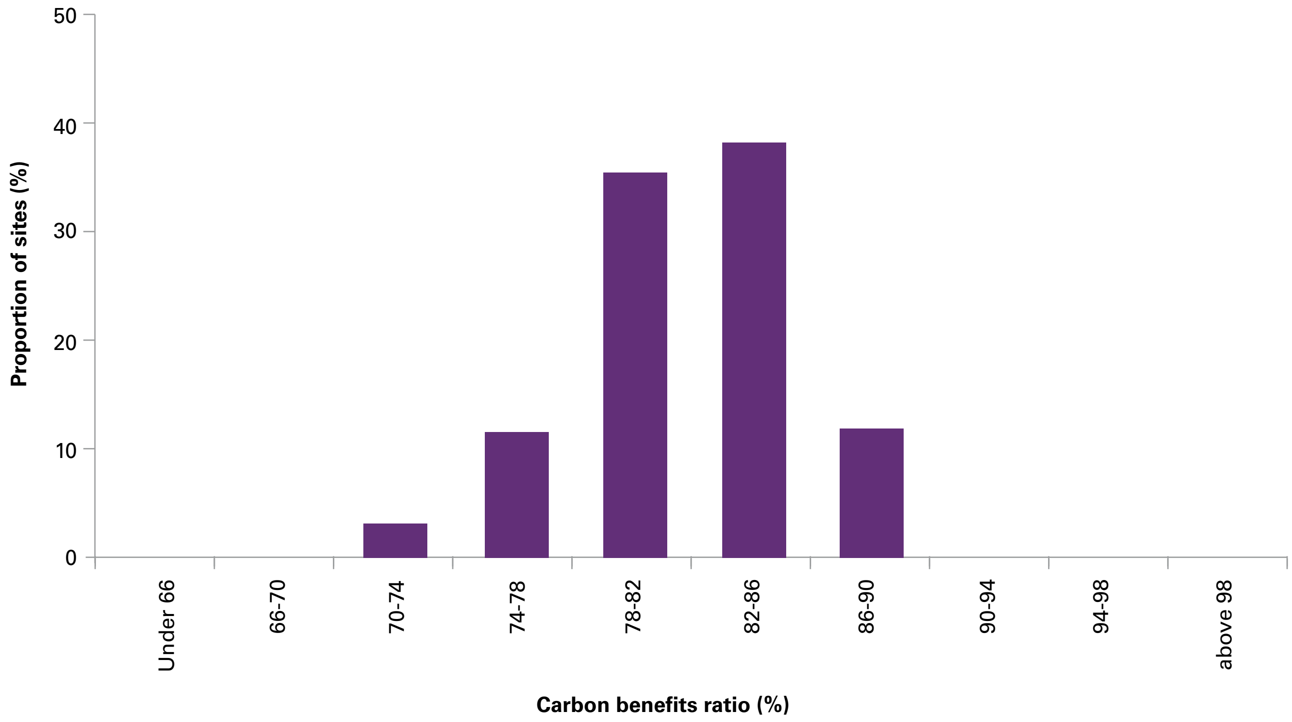



*Figure 3.3* *Comparing the annual electricity usage of difference condensing boilers*

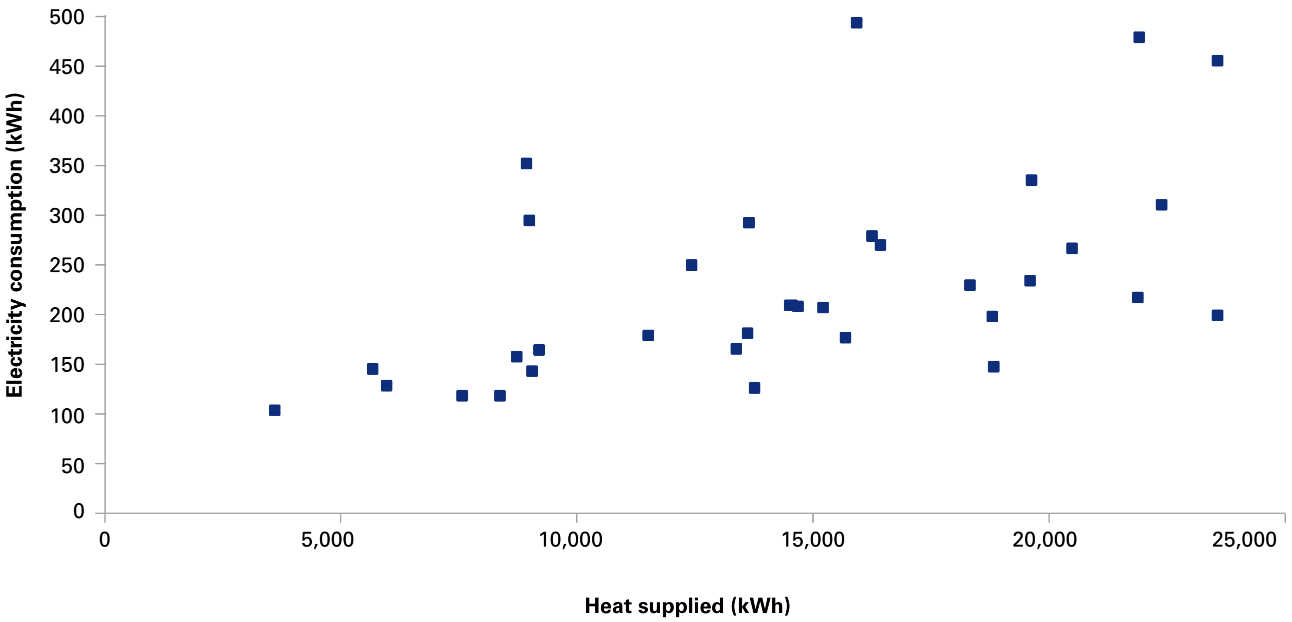


*Figure 3.2* shows the distribution of annual CBR values for the condensing boilers. The variation is similar to the thermal efficiencies, but the mean CBR is 82%, around 3% lower than the thermal efficiency due to the carbon emissions associated with the electricity consumed by the boilers.

The electrical consumption was found to vary significantly between different condensing boilers, as shown in *Figure 3.3*. To supply the space heating and hot water heat demand of a 'typical' larger home of around 20,000kWh, condensing boiler systems were observed to consume between 150kWh and 350kWh of electricity.

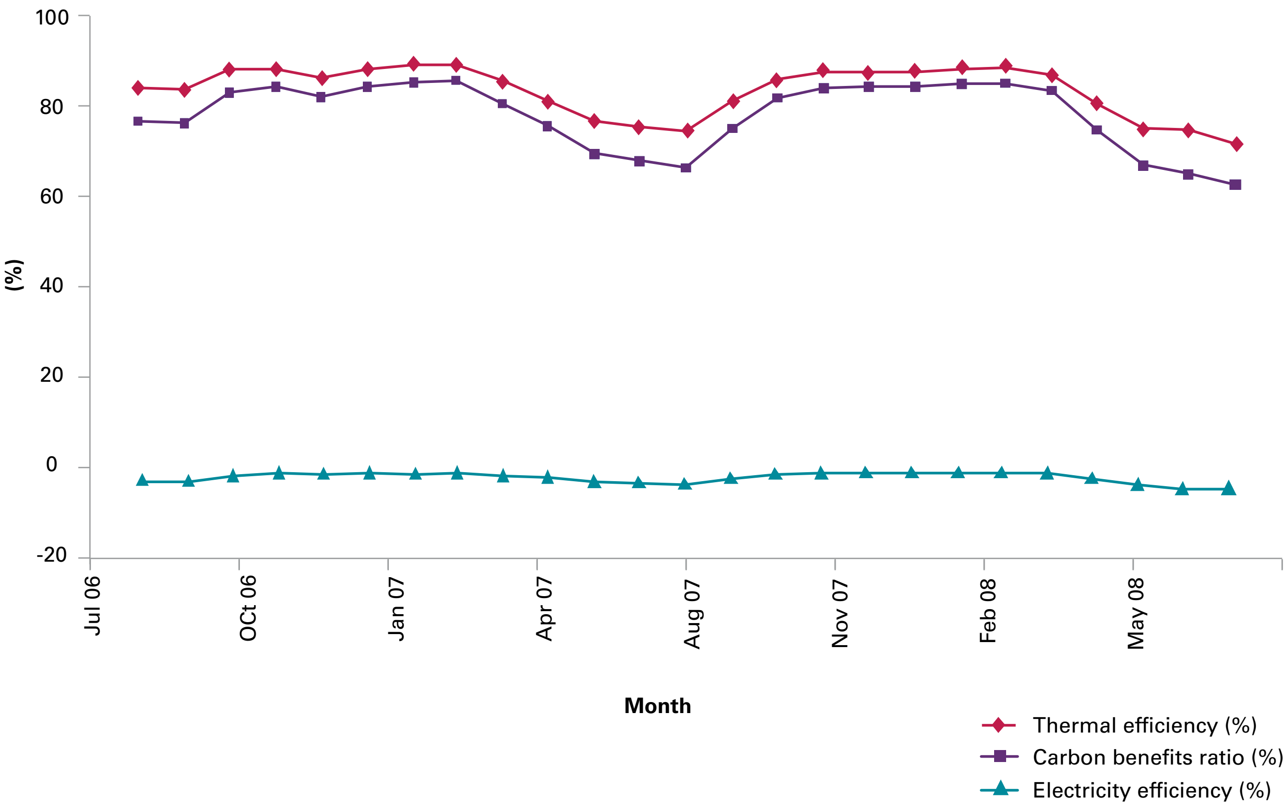
Much of this variation is believed to be attributable to the way in which the installer configures the system, and the behaviour of the householder. For example, setting the boiler thermostat below the hot water tank thermostat will cause the pump to operate for extended periods trying to heat the tank to an unachievable temperature. This sometimes occurs if the tank thermostat gets unintentionally altered within the confines of an airing cupboard.

However, the electrical consumption of ancillary components including pumps and fans, as well as standby loads, could also be reduced.

*Figure 3.4* shows the seasonal variation of the key metrics of performance.

The performance of the condensing boilers is somewhat better during the heating seasons due to the longer hours of operation and higher amount of heat generated relative to the electricity consumed.

***Figure 3.4*** *Seasonal variation in performance of condensing boilers*



## Domestic (Stirling engine) micro-CHP

*Figure 3.5* shows the distribution of annual thermal efficiency for the domestic (Stirling engine) micro-CHP systems in the field trial. The mean measured annual thermal efficiency is 71%.

As expected, the measured thermal efficiencies for the micro-CHP units are around 10-15% lower than for the condensing boilers. This is primarily a consequence of some of the heat generated by the engine being used to generate electricity.

However, the estimated loss of heat through the case of the micro-CHP systems was also significantly higher than that for the condensing boilers. This may be due to a number of factors – larger surface areas, higher surface temperatures, and some micro-CHP units being located outside the heated space of the house (e.g. in a garage).

The distribution of measured annual electrical efficiencies of the domestic micro-CHP systems in the field trial is shown in *Figure 3.6*. The mean electrical efficiency is around 6%.

The measured average heat-to-power ratio of the Stirling engine micro-CHP systems was therefore around 12:1.

The net carbon benefit of the electricity generated by the domestic micro-CHP systems is illustrated by *Figure 3.7*, which shows the distribution of measured annual CBR. The mean value is significantly higher than for the condensing boilers at 88%.

The carbon performance of the two samples is compared in more detail in section 4.

***Figure 3.5*** *Domestic micro-CHP thermal efficiency distribution (annual data)*

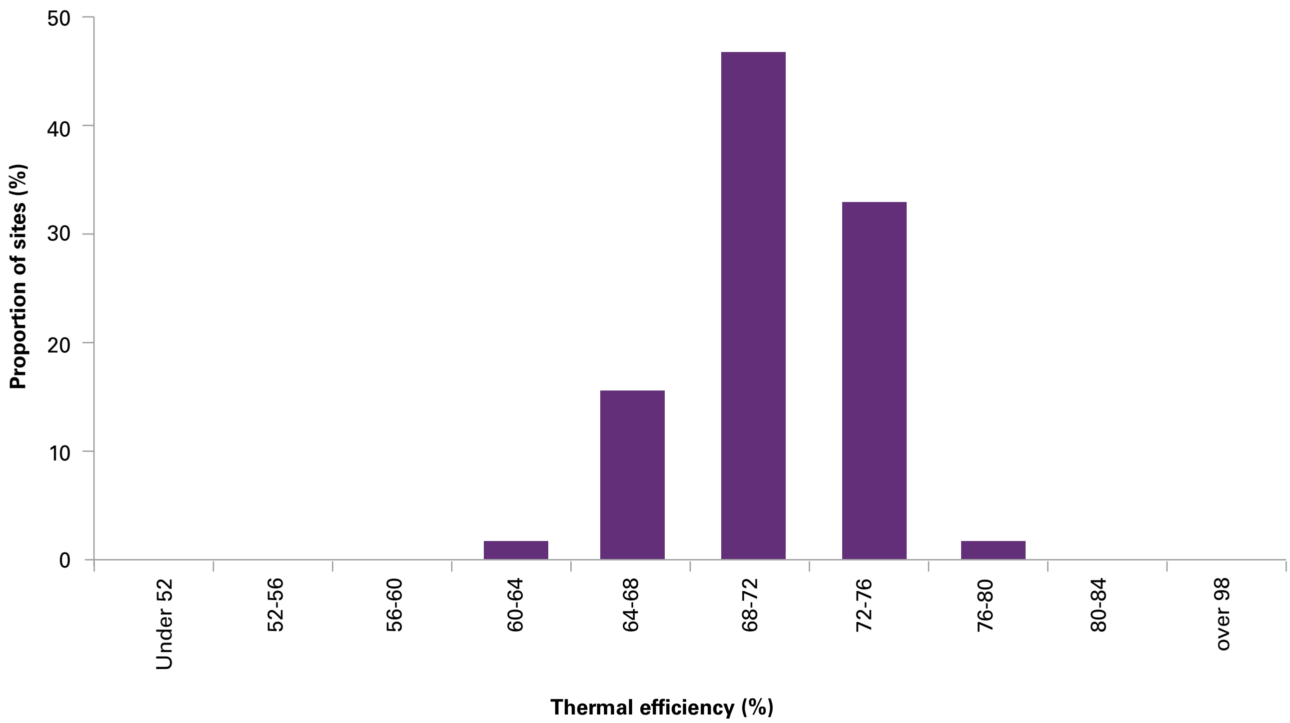


*Figure 3.6 Domestic micro-CHP electrical efficiency distribution (annual data)*

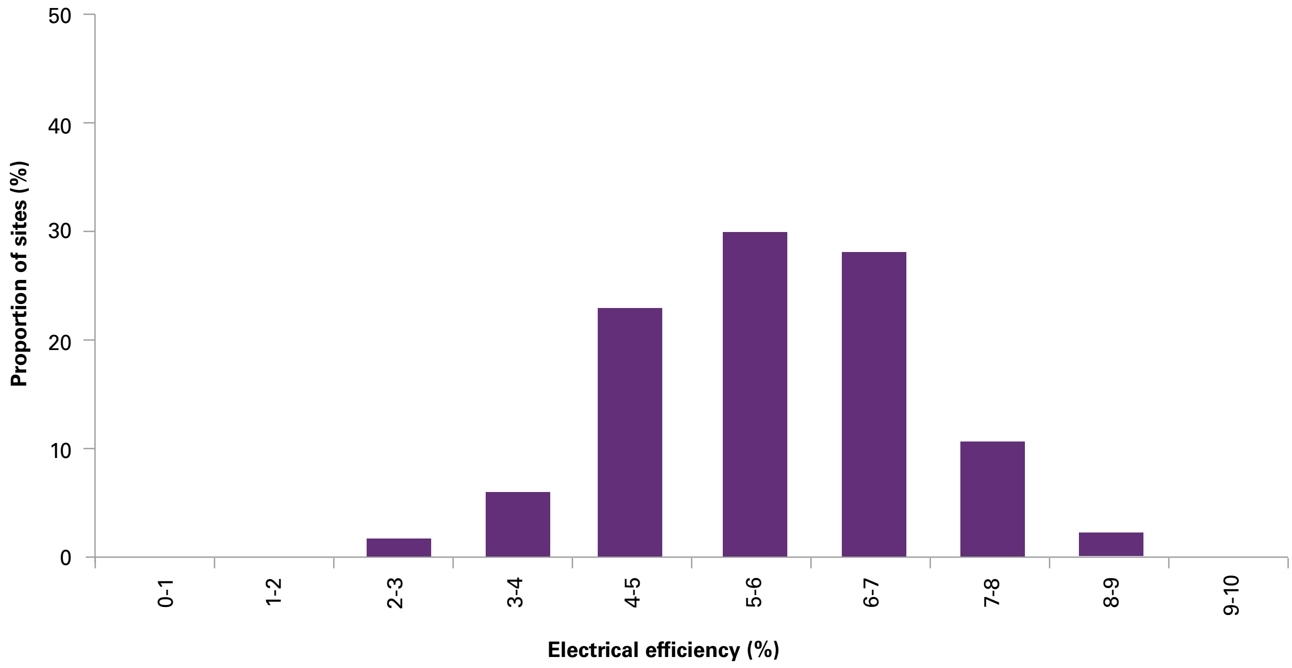
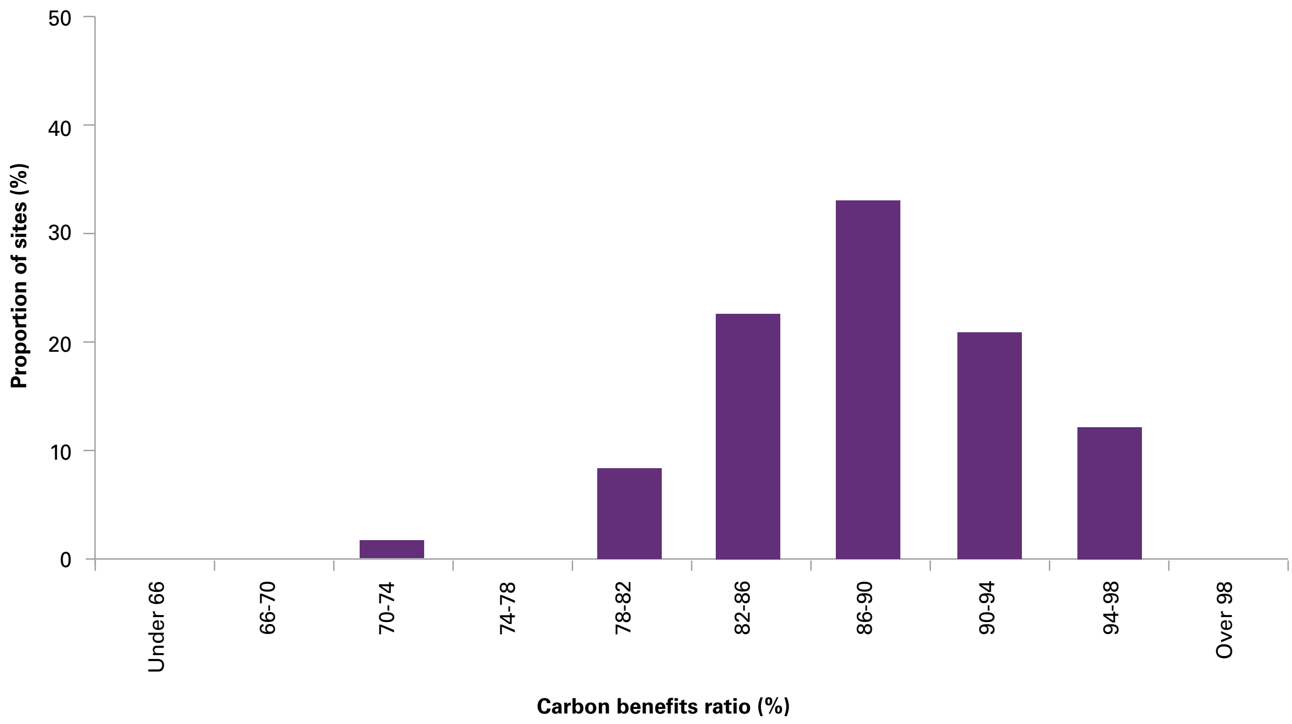



*Figure 3.7 Domestic micro-CHP CBR distribution (annual data)*



In order to account for the wide variation in performance between micro-CHP systems in the field trial, *Figure 3.8* shows the measured annual CBR values plotted against the annual heat demand. Although there is still considerable scatter, it is clear that the CBR generally improves with increased annual heat demand.

To help understand this, *Figure 3.9* shows monthly CBR values plotted against monthly heat demand. Here it becomes clear that the performance of the micro-CHP systems drops off considerably during periods of particularly low heat demand.

***Figure 3.8*** *Variation in CBR with annual heat demand for domestic micro-CHP*

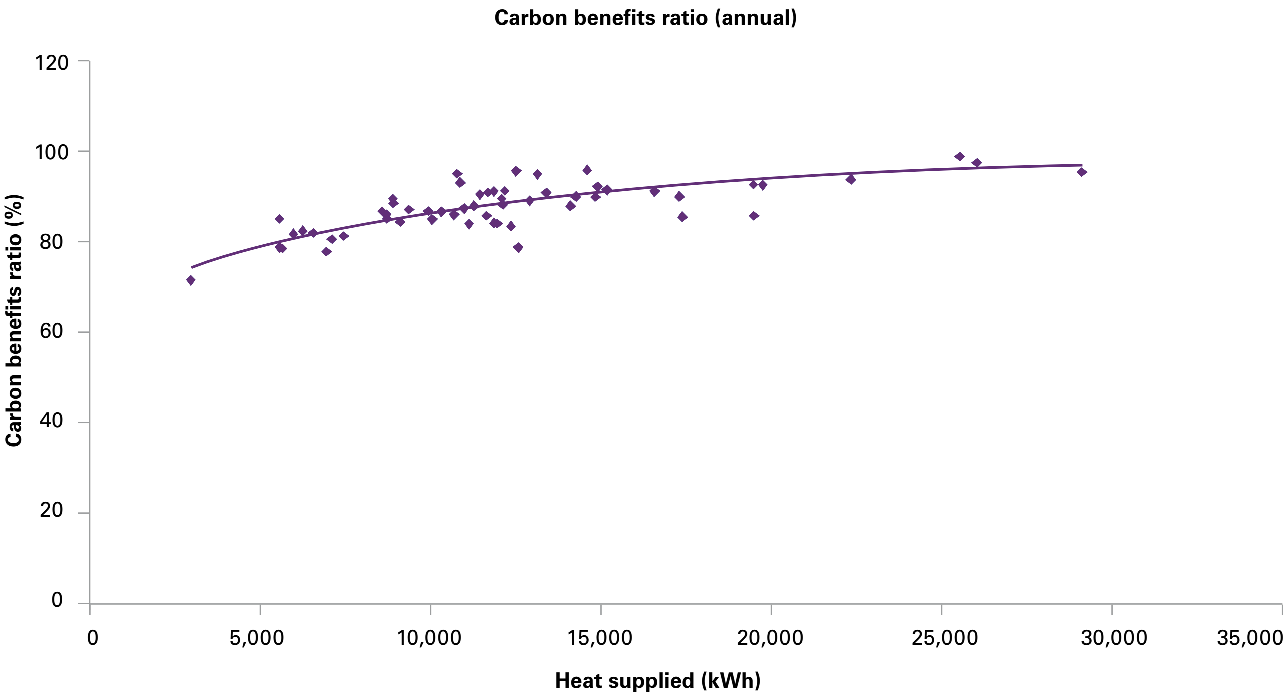
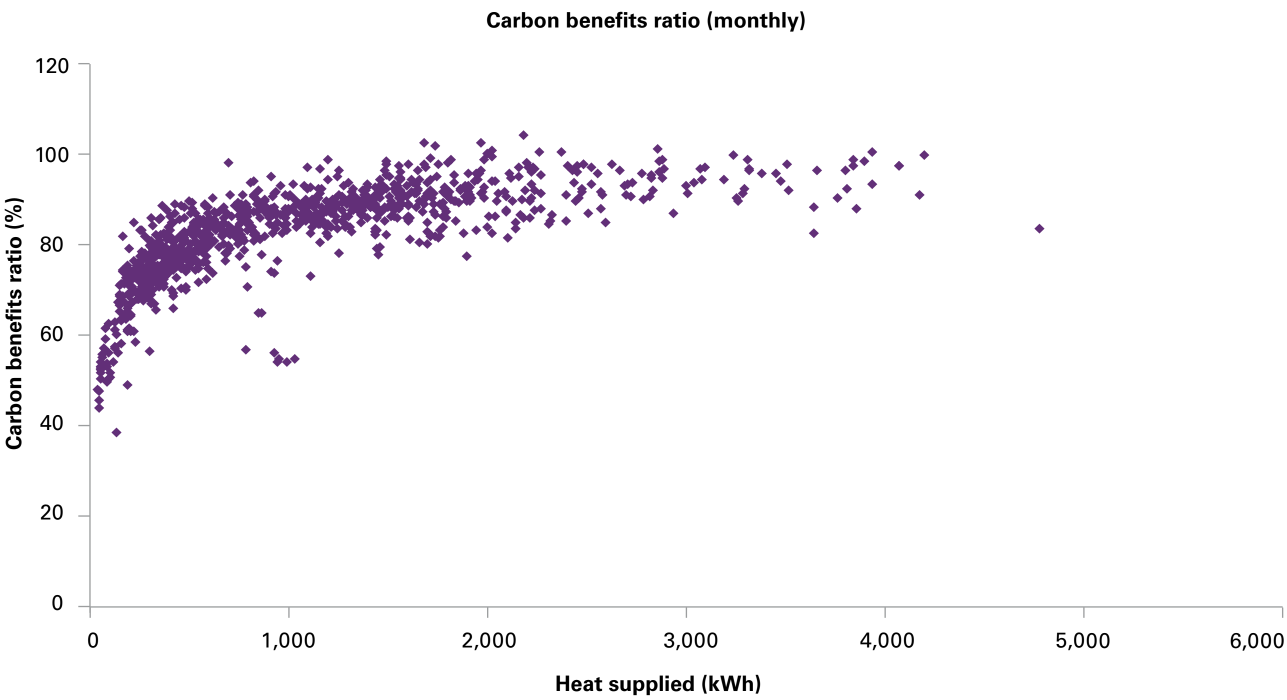



***Figure 3.9*** *Variation in CBR with monthly heat demand for domestic micro-CHP*



Analysis of detailed five-minute data in the Interim Report showed that the dependence of micro-CHP performance on heat demand can to a large extent be explained in terms of the importance of longer operating cycles in achieving efficient operation.

Due to the electricity consumed in start-up and shut-down either side of an operating cycle, the analysis showed that current Stirling engine micro-CHP units typically need to operate for a minimum cycle length of over one hour (from start of gas use to end of electrical generation) to provide an overall carbon saving benefit relative to a condensing boiler. Shorter, inefficient operating cycles are more likely to be observed during periods of low heat demand.

Performance would therefore be expected to be relatively poor for systems installed in households with relatively low heat demands, and for all systems during the summer months. *Figure 3.10* shows the seasonal variation in performance of the micro-CHP systems during the field trial – clearly showing a major decline in performance during the summer months.

## Small commercial (IC engine) micro-CHP

Only a small number of systems completed a full 12 months of continuous operation during the field trial. All the systems were configured as the lead boiler in a plant room, and therefore operated with consistently high running hours throughout the year. Hence the data presented in this section are for monthly performance, to provide a more statistically relevant sample.

*Figure 3.11* shows the distribution of measured monthly thermal efficiency for the small commercial (IC engine) micro-CHP systems in the field trial. *Figure 3.12* shows the corresponding distribution of measured monthly electrical efficiencies.

***Figure 3.10*** *Seasonal variation in performance of micro-CHP systems*

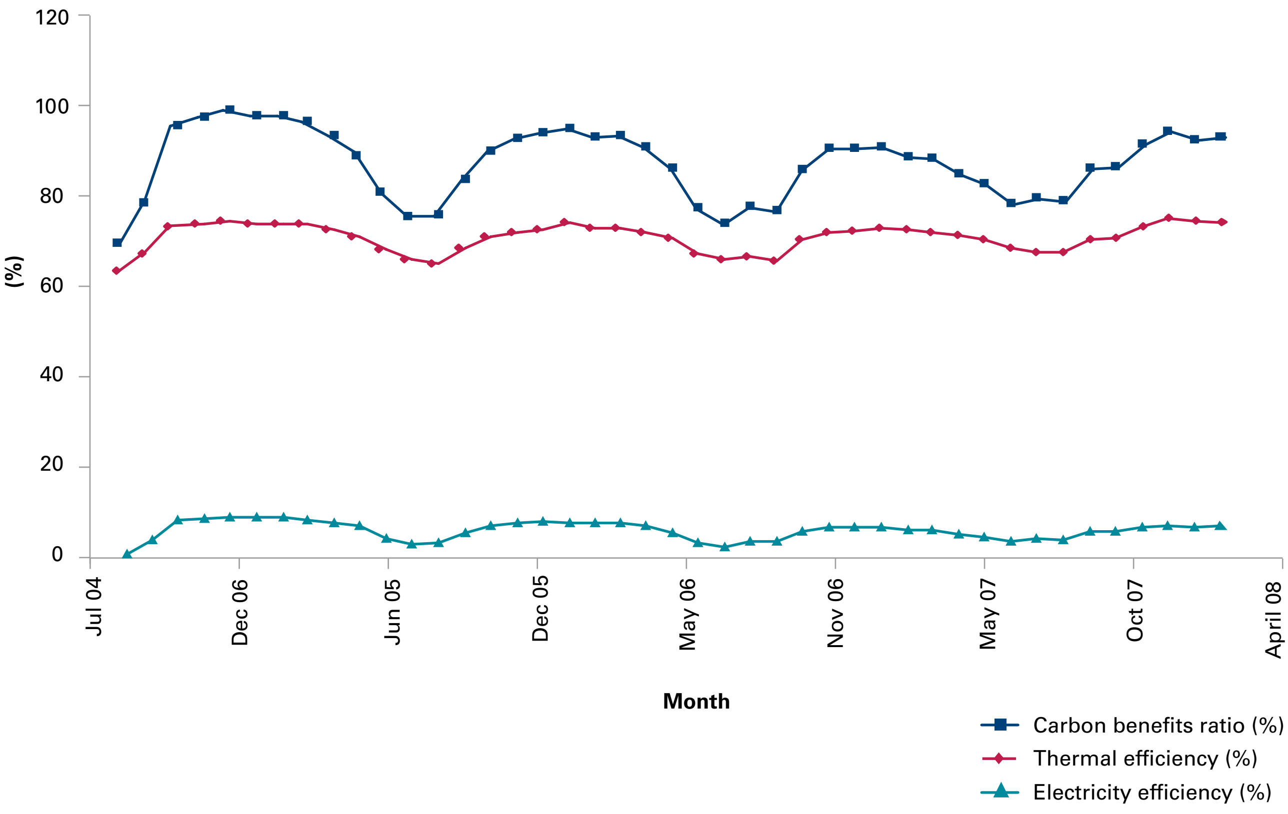


***Figure 3.11*** *Small commercial micro-CHP thermal efficiency distribution (monthly data)*

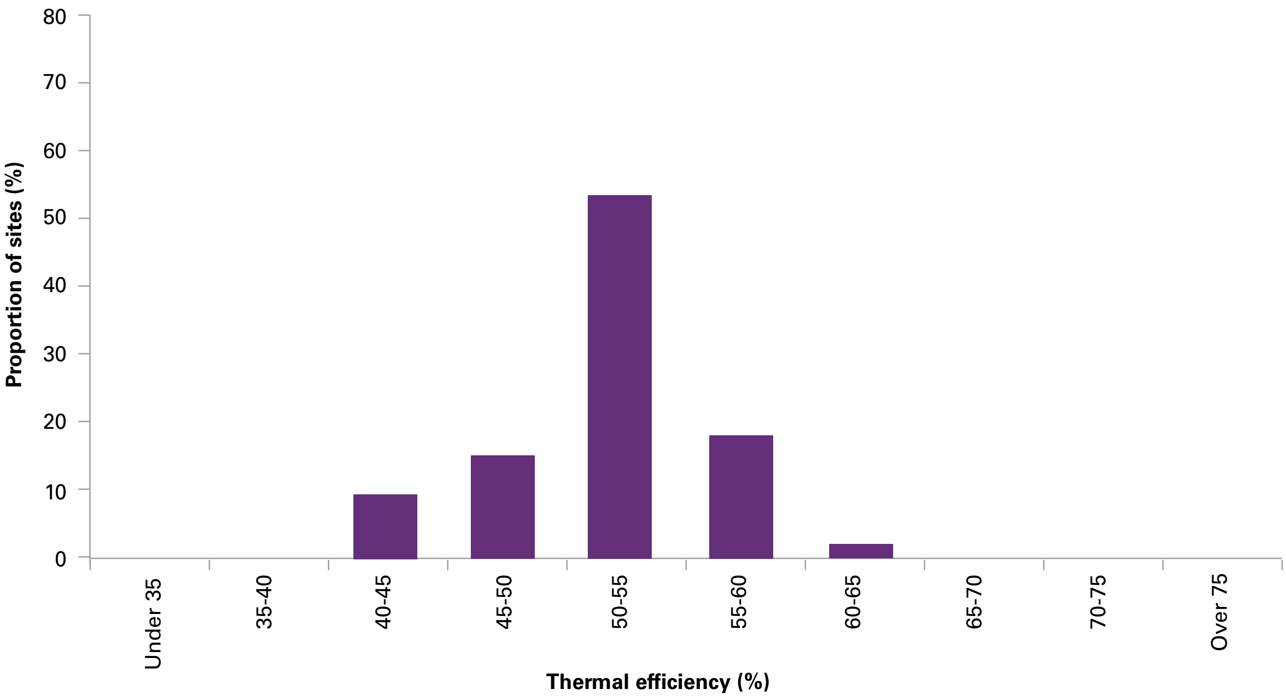



***Figure 3.12*** *Small commercial micro-CHP electrical efficiency distribution (monthly data)*

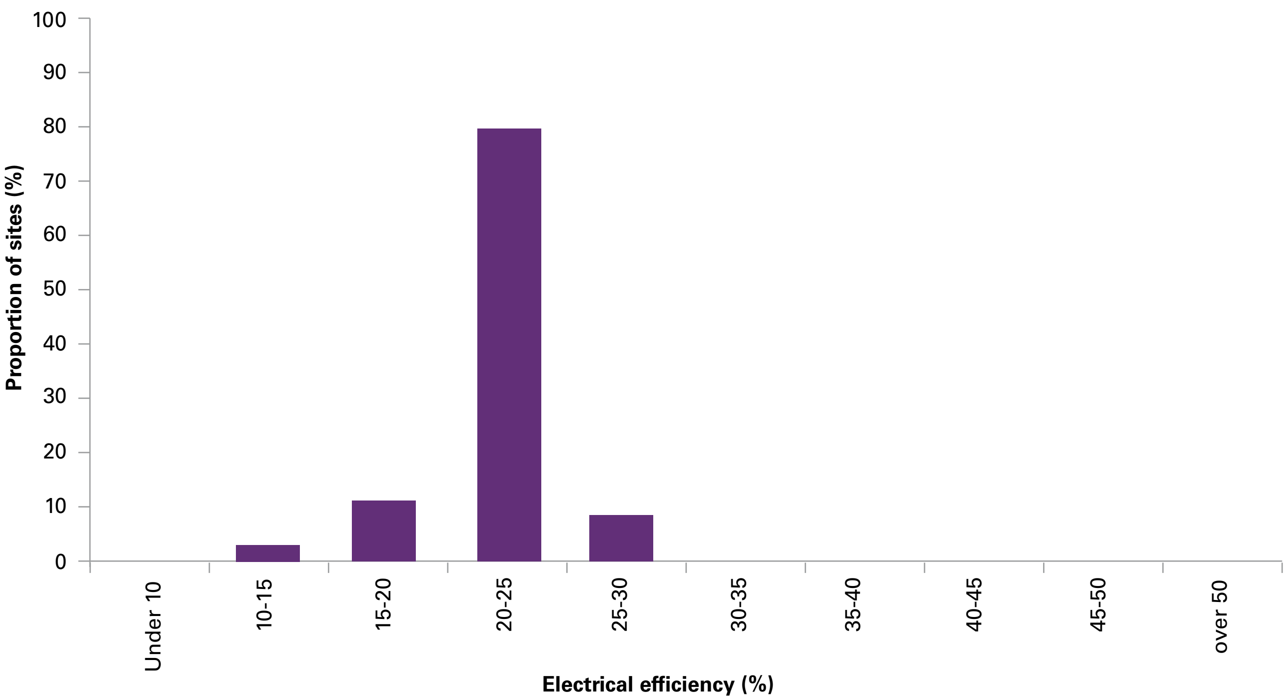
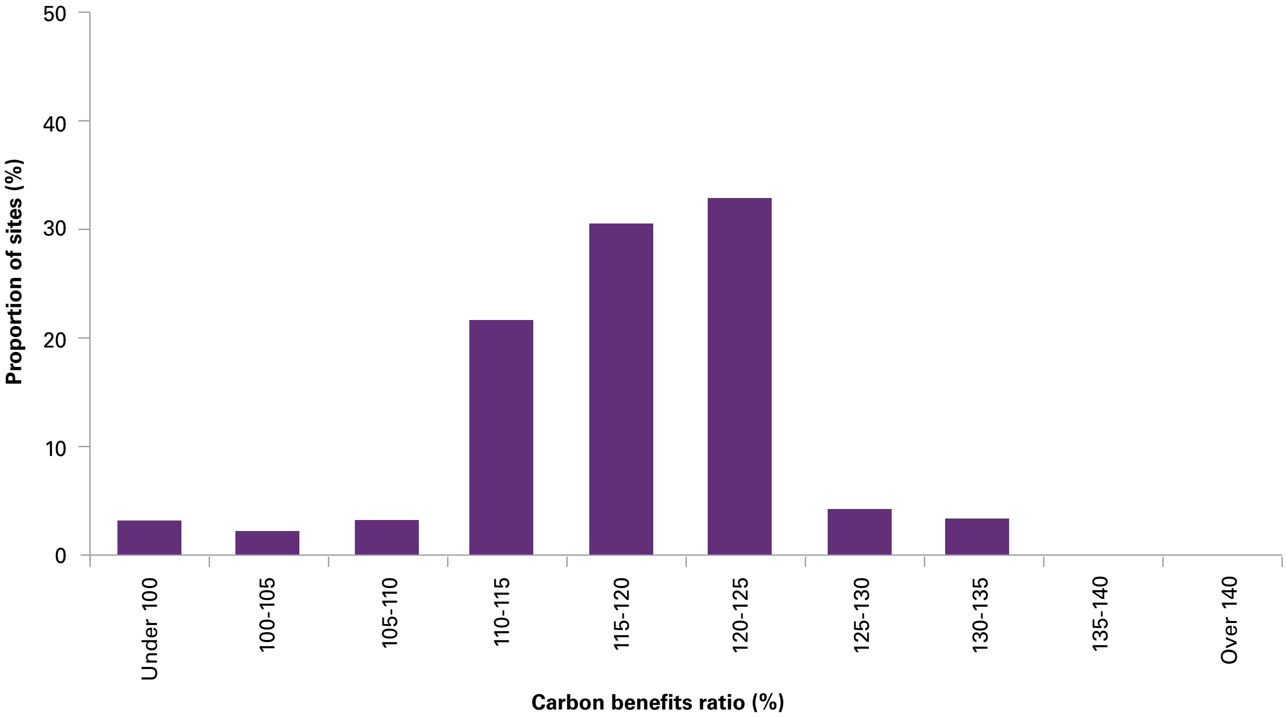


***Figure 3.13*** *Small commercial micro-CHP carbon benefits ratio distribution (monthly data)*




As expected, the thermal efficiencies of the IC engines are much lower than measured for the domestic (Stirling engine) systems, and the electrical efficiencies are correspondingly higher, as these systems are designed to have lower heat to power ratios. The mean thermal efficiency was 52%, while the mean electrical efficiency was 22%. The small commercial micro-CHP systems were therefore found to achieve a typical measured heat-to-power ratio of around 2.3.

The result of this much lower heat to power ratio in terms of carbon emissions is shown in *Figure 3.13*. The mean monthly CBR for the small commercial micro-CHP systems is 117% – much higher than for the domestic micro-CHP or condensing boilers.

*Figure 3.14* shows the monthly CBR values plotted against the monthly heat demand – the two appear to be almost entirely independent. This is because commercial systems are sized to cover the base load heating and hot water requirements. As a result, these systems tend to operate for similar, extended periods all year round.

As expected, *Figure 3.15* shows no clear seasonal variation in performance. Note that a number of apparent anomalies on this figure (e.g. July 2006) are explained by the fact that valid data was obtained for only one or two of the systems in those months, resulting in 'noisy' data.

*Figure 3.14* *Variation in CBR with monthly heat demand for small commercial micro-CHP*

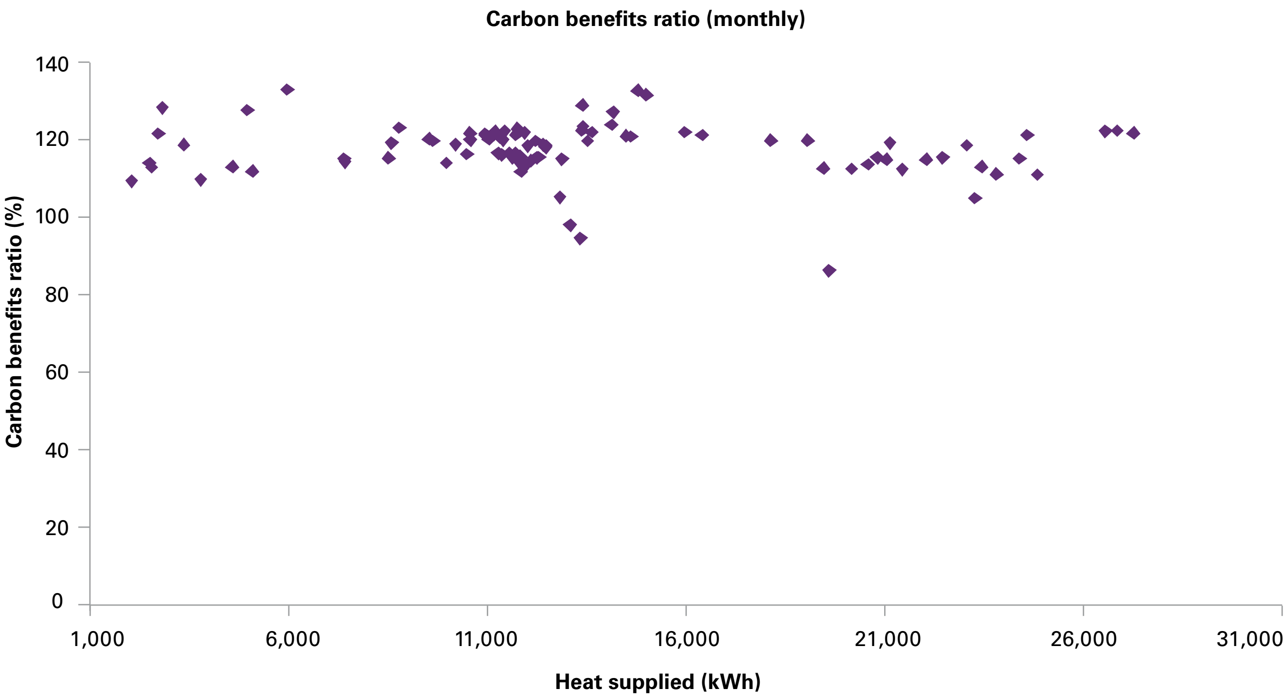
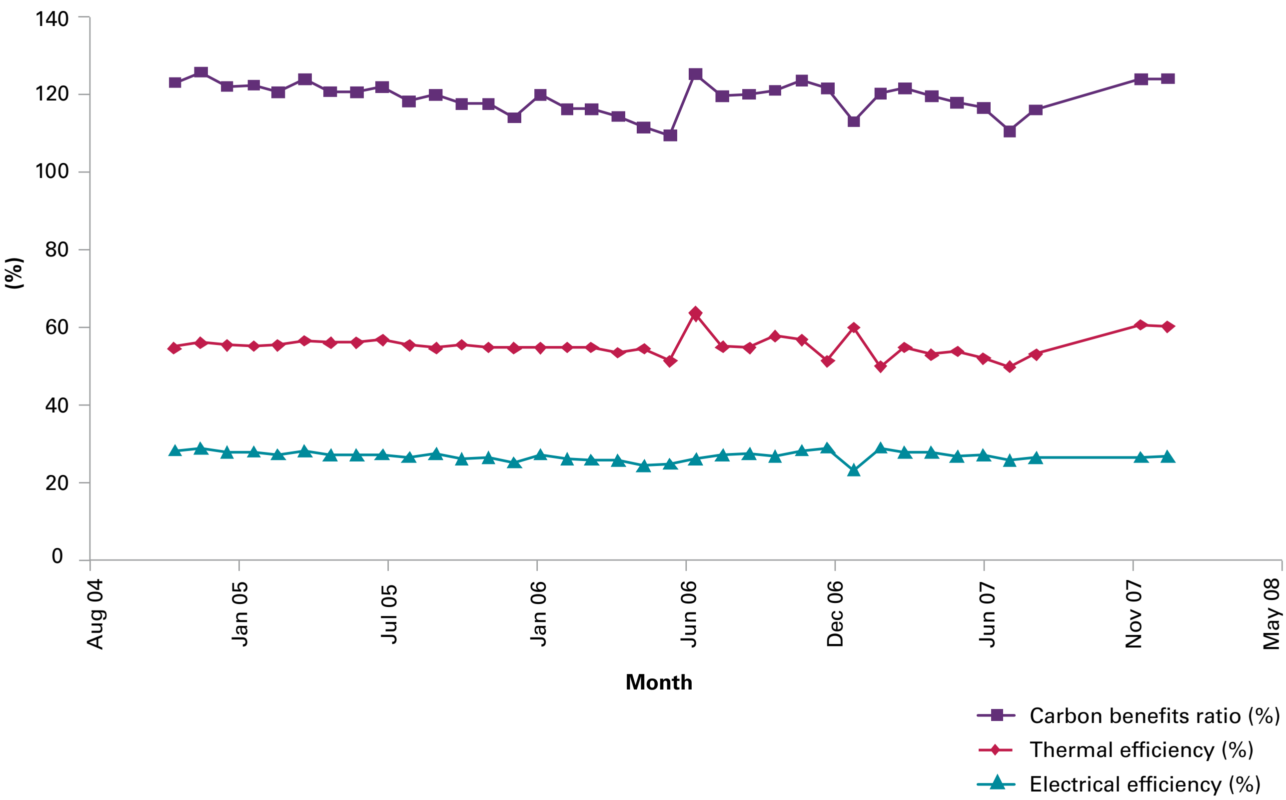



*Figure 3.15* *Seasonal variation in performance of small commercial micro-CHP systems*

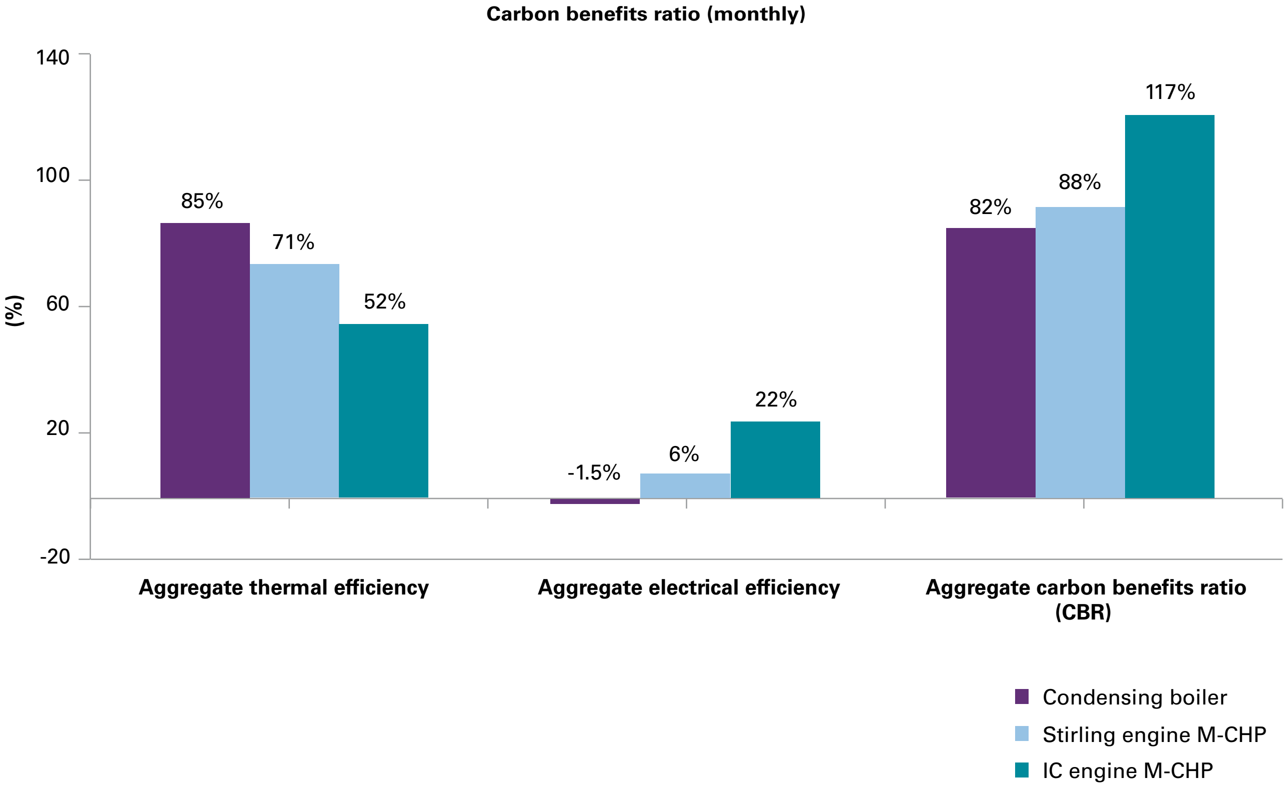


## Summary

*Figure 3.16* shows a summary of the mean thermal efficiency, electrical efficiency and carbon benefits ratio of the three types of heating system in the field trial:

- domestic Stirling engine micro-CHP
- domestic condensing boilers
- and small commercial IC engine micro-CHP.

***Figure 3.16** Summary of mean efficiencies and CBRs*



# 4. Analysis of results

The previous section presented the results of the field trials of condensing boilers and micro-CHP systems in domestic and small commercial installations separately from each other. In this section we compare these sets of results in order to draw conclusions regarding the overall benefits of micro-CHP systems over condensing boilers.

Note that throughout this section the comparisons drawn are directly relevant only for Stirling engine (domestic) and IC engine (small commercial) micro-CHP systems with characteristics similar to those in the field trial. Both the estimated carbon savings and trends in performance are likely to vary for different models and types of micro-CHP system.

A key driver of carbon emissions associated with the demand for space heating in a particular household or business is the difference between the internal temperature demanded by the occupants through the control system and the external temperature. It would not be reasonable to compare the carbon emissions of two different types of heating system if they did not deliver the same internal temperature in the building, or if one was located in a much colder part of the world.

*Figure 4.1* therefore compares the average internal and external temperatures of the domestic condensing boiler and micro-CHP sites over the period from August 2006 to February 2008[8].

The figure shows that, while the average external temperatures of the two samples were very similar, the households with domestic micro-CHP heating systems had slightly higher internal temperatures than the boiler sites

This difference in the average internal temperature was driven by a group of new-build properties in the field trial at which unusually high internal temperatures were recorded and may not be representative. However, it may indicate that a ‘rebound effect’ was present, in which householders tend to take up some of the benefit of a more efficient heating system as improved comfort, rather than lower energy bills[9].

The effect could be significant – the Energy Saving Trust estimates that turning down a room thermostat by 1°C can cut up to 10% off domestic heating bills – and so the theoretical potential of micro-CHP may be underestimated in the analysis that follows. However, the results have not been adjusted to account for this effect, to ensure that they are representative of what happens when micro-CHP systems are used in real households, and the control settings that real users choose to apply.

## Domestic heating systems

In this section, comparisons are made between the performance of condensing boilers and micro-CHP systems in domestic applications. *Figure 4.2* compares the distributions of the carbon benefits ratios for the boiler and micro-CHP samples.

[8] This represents the period over which a significant number of both boiler and micro-CHP units were in service.

[9] For more explanation of rebound effects see www.ukerc.ac.uk/Downloads/PDF/07/0710ReboundEffect/0710ReboundEffectReport.pdf

*Figure 4.1 Comparison of average internal and external temperatures for condensing boiler and micro-CHP sites*

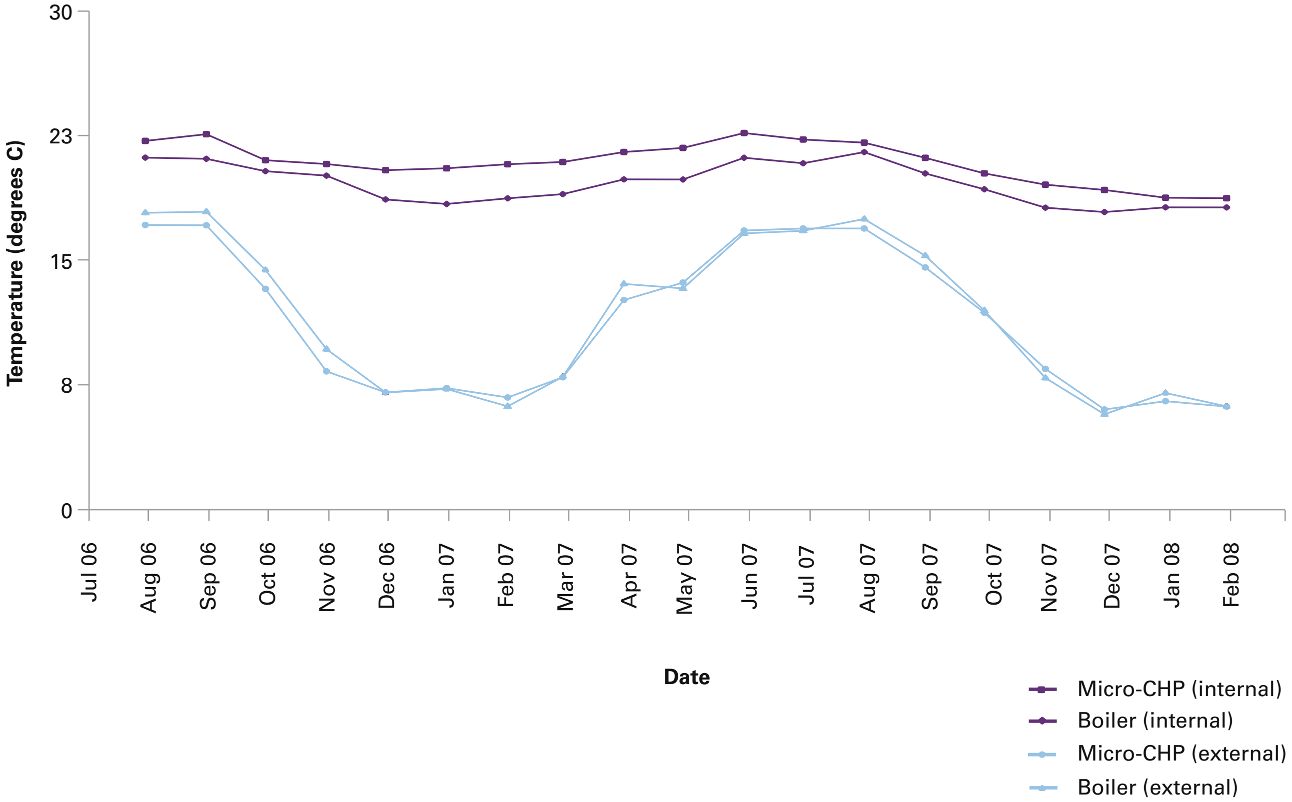
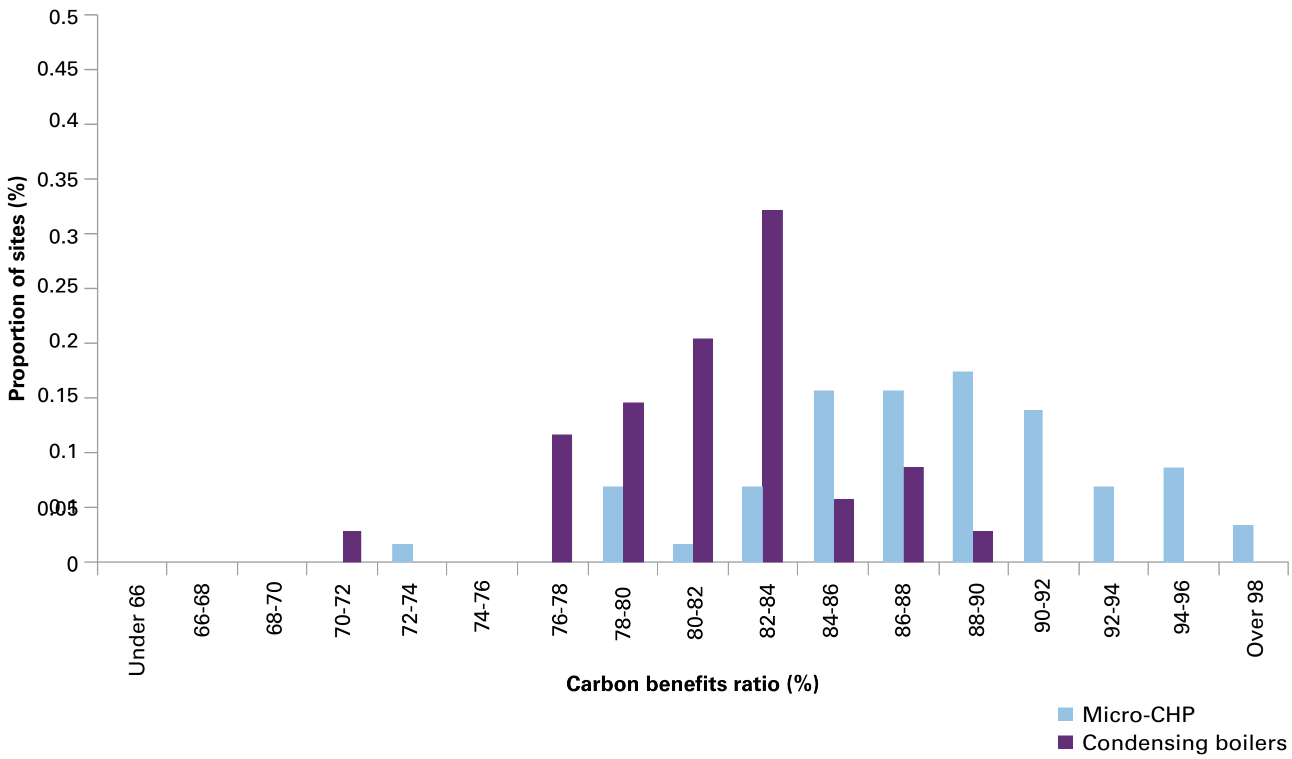



*Figure 4.2 Comparison of distributions of carbon benefits ratio for domestic condensing boilers and micro-CHP systems*



Comparing the two distributions shows that typically the micro-CHP systems have higher carbon benefits ratios than the condensing boilers, but that there is considerable variation between individual installations and that in some cases a micro-CHP system may have lower CBR than an equivalent condensing boiler.

## Overall savings

By comparing the total heat supplied and total carbon emissions of the two populations, we can estimate the aggregate carbon saving that would result from substituting the micro-CHP units in the field trial for condensing boilers across the UK housing stock. This value should be useful for policy makers considering the net benefit of promoting the growth of micro-CHP in the domestic heating market.

As shown in *Figure 4.3*, the aggregate carbon saving is estimated to be around 5%. The range of uncertainty on this difference is estimated to be around ±1%[10].

## Savings for an individual installation

An alternative approach is to compare randomly selected condensing boiler sites from the field trial with randomly selected micro-CHP sites. We can then examine the statistical distribution of the difference between the performances of the two heating systems. This is roughly analogous to the situation faced by an individual householder making a choice between the two types of heating system who asks: "what is the chance that my micro-CHP system will save carbon relative to a condensing boiler?"

This comparison has been made by fitting representative probability distributions to the distributions of annual performance of the condensing boiler and micro-CHP systems in the field trial. Monte Carlo simulation has been used to estimate the mean and variance of the savings realised by substituting a condensing boiler for a micro-CHP system.

Using this method, the mean carbon saving for an individual installation is estimated to be around 4%. However, the likely range of savings in an individual installation is from -4% to 12%[11]. This large uncertainty indicates that there is a significant probability (around one in three) that for an individual installation, the micro-CHP system will actually lead to higher carbon emissions than a condensing boiler.

***Figure 4.3***

| | Condensing boilers | Micro-CHP | |
|---|---|---|---|
| Total $CO_2$ emissions | 117,023kg$CO_2$ | 157,856 kg$CO_2$ | |
| Total heat supplied | 494,709kWh | 702,462kWh | Difference |
| Mean carbon intensity of heat supplied | 0.237kg$CO_2$/kWh | 0.225 kg$CO_2$/kWh | 5% |

[10] An approximation to the standard deviation of this difference between the means of the two populations is estimated from their standard deviations using the following formula: $o=(o^2_1/n_1+o^2_2/n_2)^{-½}$

[11] Throughout this section, the "likely range" is defined as being within 1 standard deviation of the mean value.

[12] Due to the considerable uncertainties involved, these figures are quoted to one significant figure.

For a 'typical' annual heat demand for a larger house of around 20,000kWh, this equates to an absolute annual carbon saving in the approximate range -200kg to 600kg per year, with a mean saving of 200kg[12].

Note that the aggregate saving, which compares the total carbon emissions per kWh of heat supplied across the two samples, gives a higher percentage saving than comparing at the level of individual households. This is because this approach effectively weights the households with higher heat demands more highly. As has been shown in previous sections, these households are typically those in which micro-CHP systems perform relatively well so the aggregate percentage carbon saving is higher.

## Variation of carbon savings with heat demand

It has been shown in the previous sections and the Interim Report that micro-CHP systems perform better in sites with a high heat demand, while boiler performance is relatively independent of the total heat demand of the site. It is therefore anticipated that the greatest carbon savings will be realised in sites with higher heat demands.

*Figure 4.4* compares the annual carbon emissions of micro-CHP and condensing boiler installations with the annual demand. As would be expected, both relationships are roughly linear. However, at lower heat demands (less than around 10,000kWh/year), there is no clear difference between the annual carbon emissions of the two types of heating system for a given annual heat demand. At higher heat demands (above around 15,000kWh/year) the difference becomes much more consistent.

***Figure 4.4** Carbon emissions versus heat demand (domestic)*

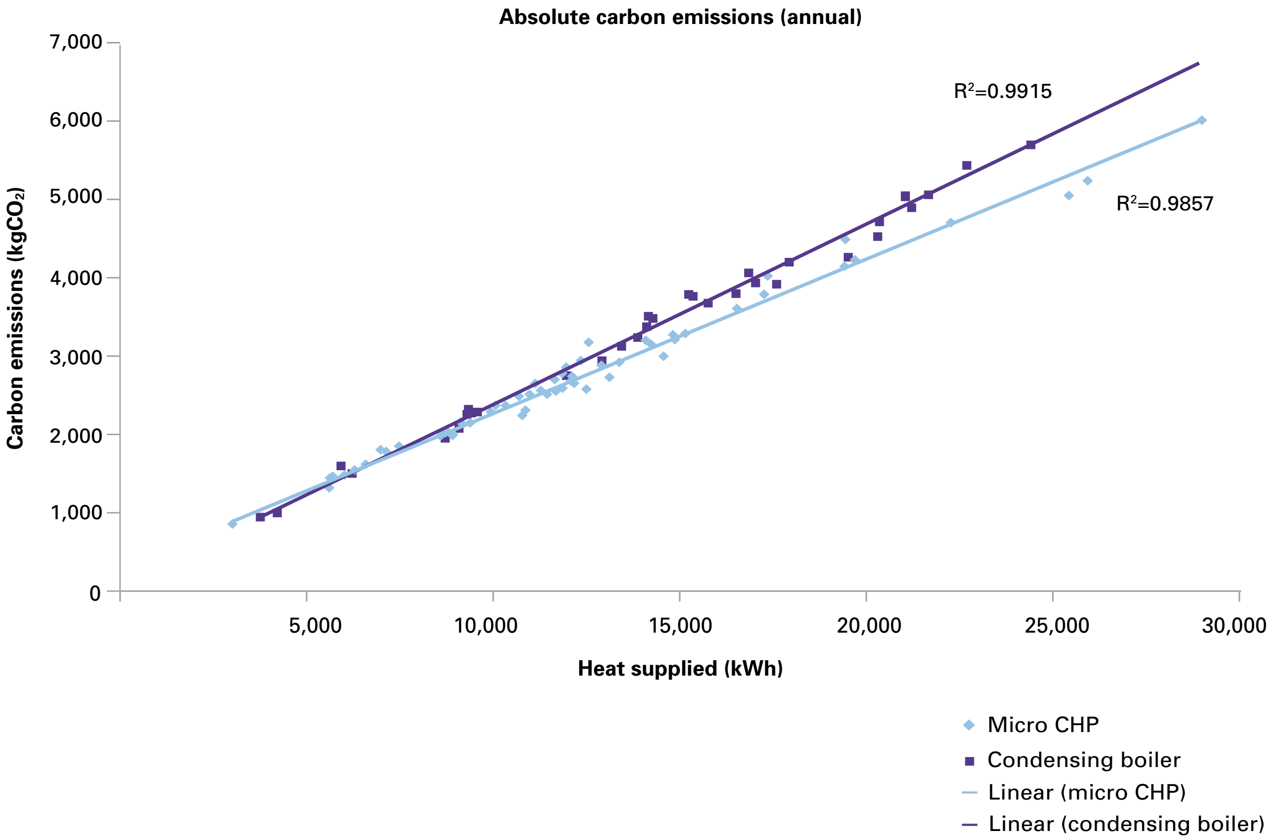
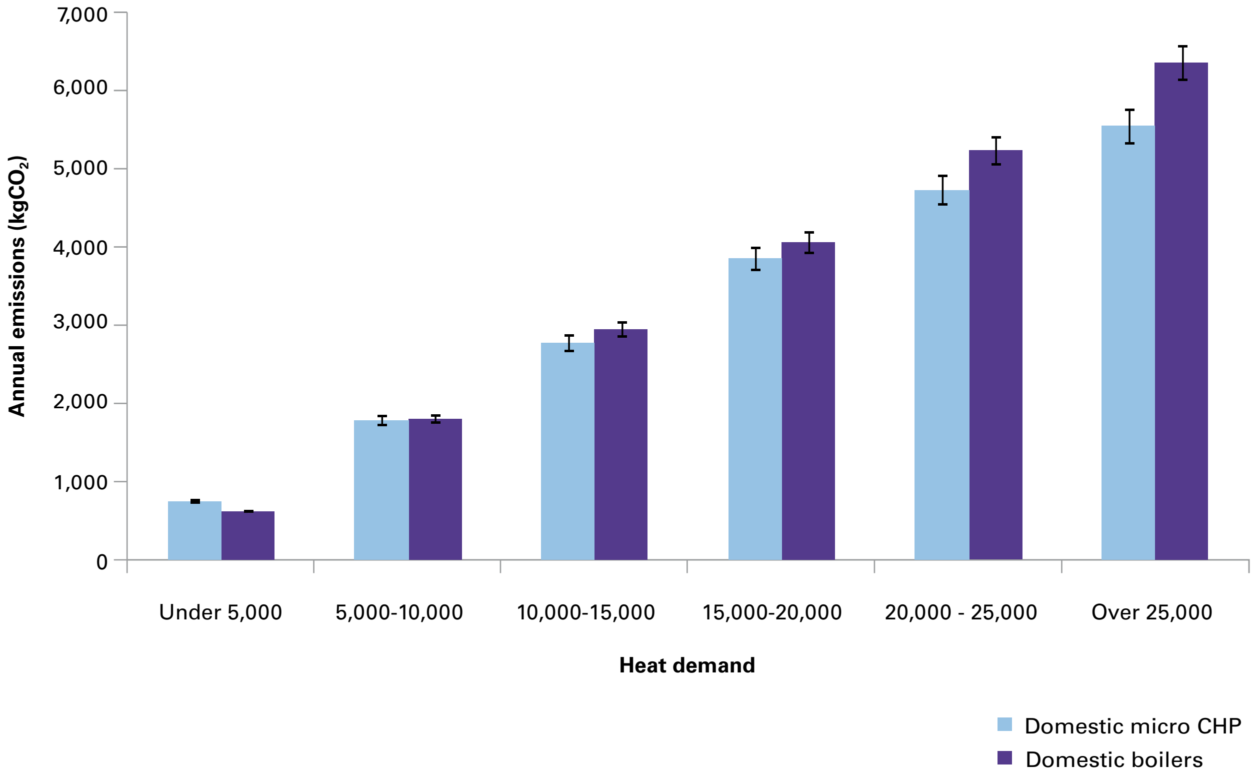


***Figure 4.5** Carbon emissions versus heat demand 'bins'*




A significant reduction in carbon emissions is much more likely to be achieved when substituting the Stirling engine micro-CHP systems in the field trial for condensing boilers in houses with high heat demands.

In order to estimate the likely carbon savings for households with different levels of heat demand, *Figure 4.5* shows the mean and standard deviation for groups of micro-CHP and condensing boiler sites with similar annual heat demands.

The figure shows that for households with annual heat demands above around 15,000kWh, it is very likely that substituting a micro-CHP system for a condensing boiler will lead to a material carbon saving. Comparing all the households in the field trial with an annual heat demand of over 15,000kWh, the aggregate saving, estimated by comparing the carbon intensity of heat supplied in the two samples, is around 9%.

Using the same statistical approach as described above, the mean carbon saving for an individual site with an annual heat demand >15,000kWh is estimated to also be around 9%, with a likely range of between 4% and 14%. For a 'typical' large house with an annual heat demand of around 20,000kWh, this represents an absolute annual carbon saving of between 200kg and 700kg per year, with a mean of around 400kg. However, although the general trend is robust, it should be noted that the sample sizes in this case are relatively small (17 boilers and 11 micro-CHP units) so the results should be treated with some caution.

## Types of household

By comparing the characteristics of the households in the field trial with the measured annual heat demands, it is possible to draw some conclusions about the types of household in which micro-CHP systems are most likely to lead to significant carbon savings.

*Figures 4.6* to *4.9* show how the number of bedrooms, floor area, form (detached, terraced, etc) and age of the houses in the field trial relate to their annual heat demand, for those sites for which the relevant characteristics are known.

***Figure 4.6*** *Heat demand vs. number of bedrooms*

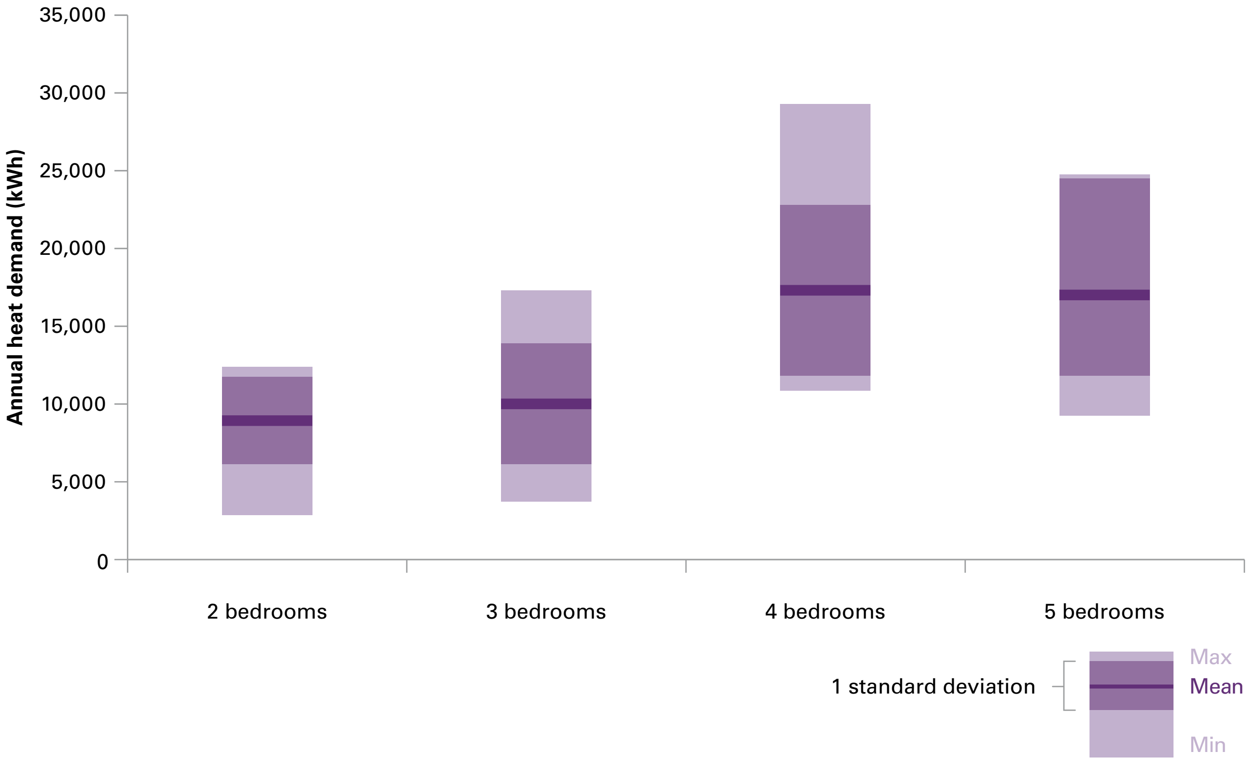



***Figure 4.7*** *Heat demand vs. floor area*

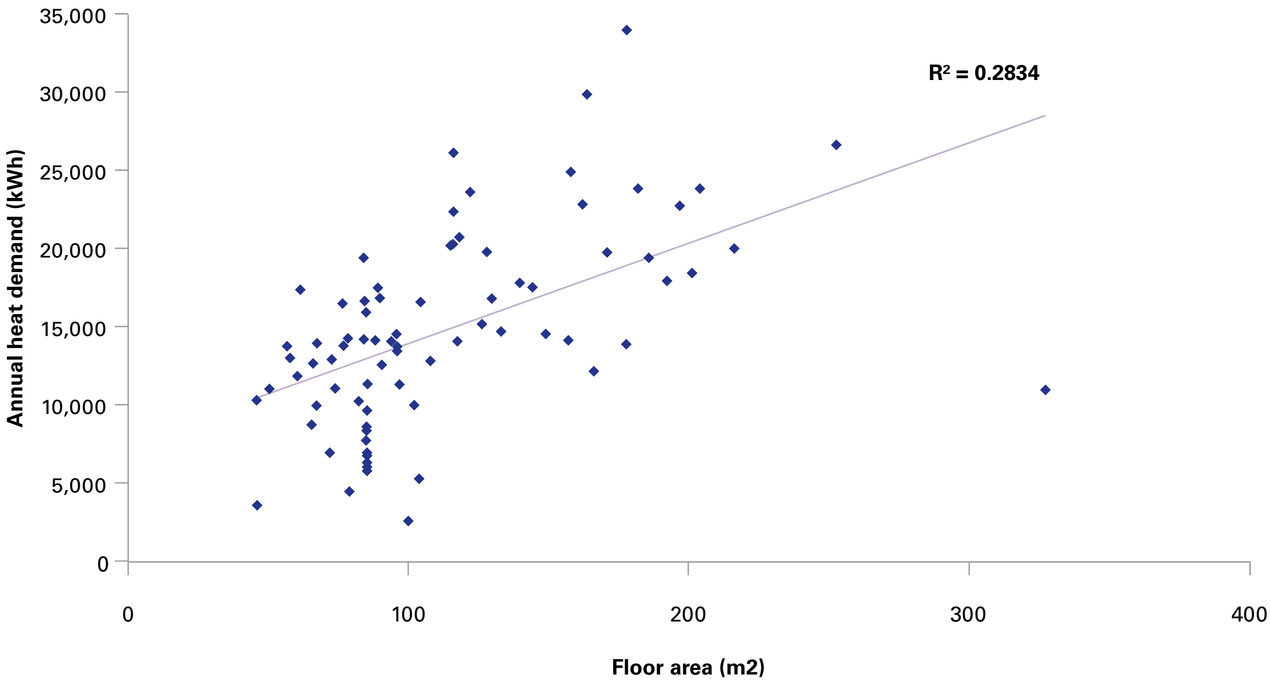


*Figure 4.8* *Heat demand vs. type of household*

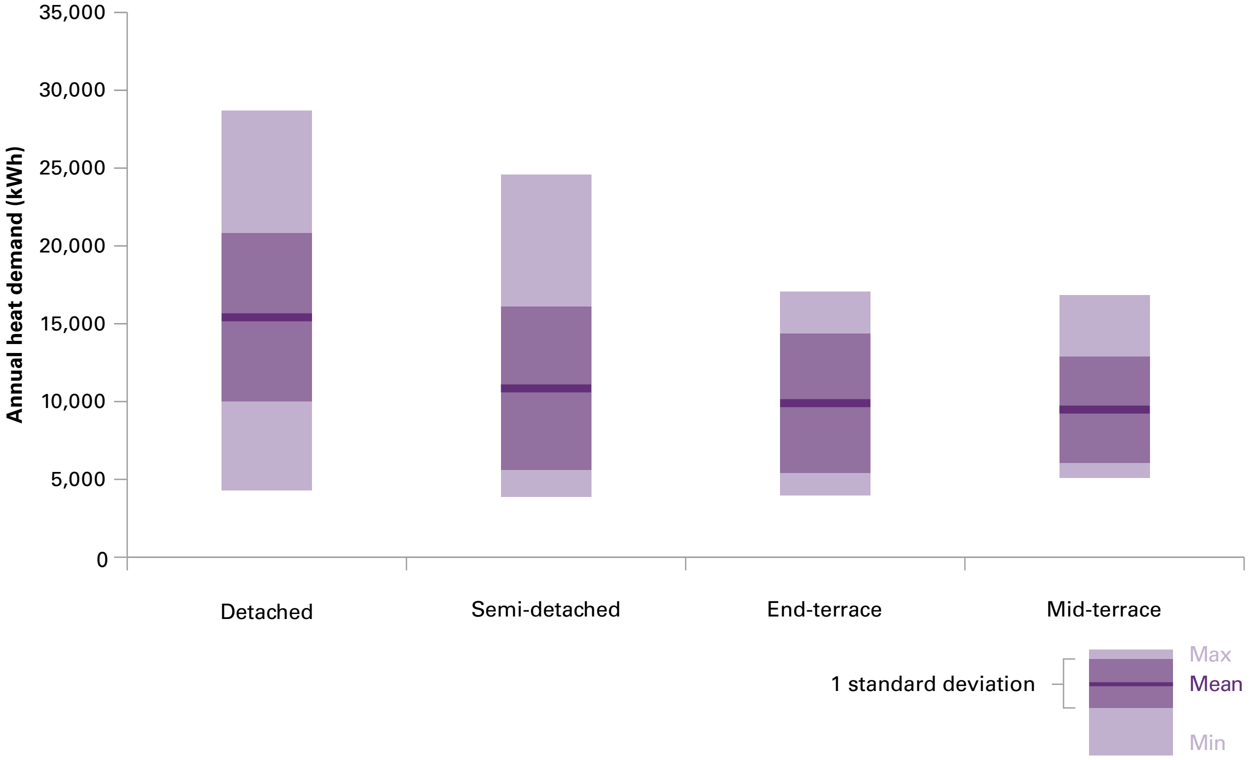
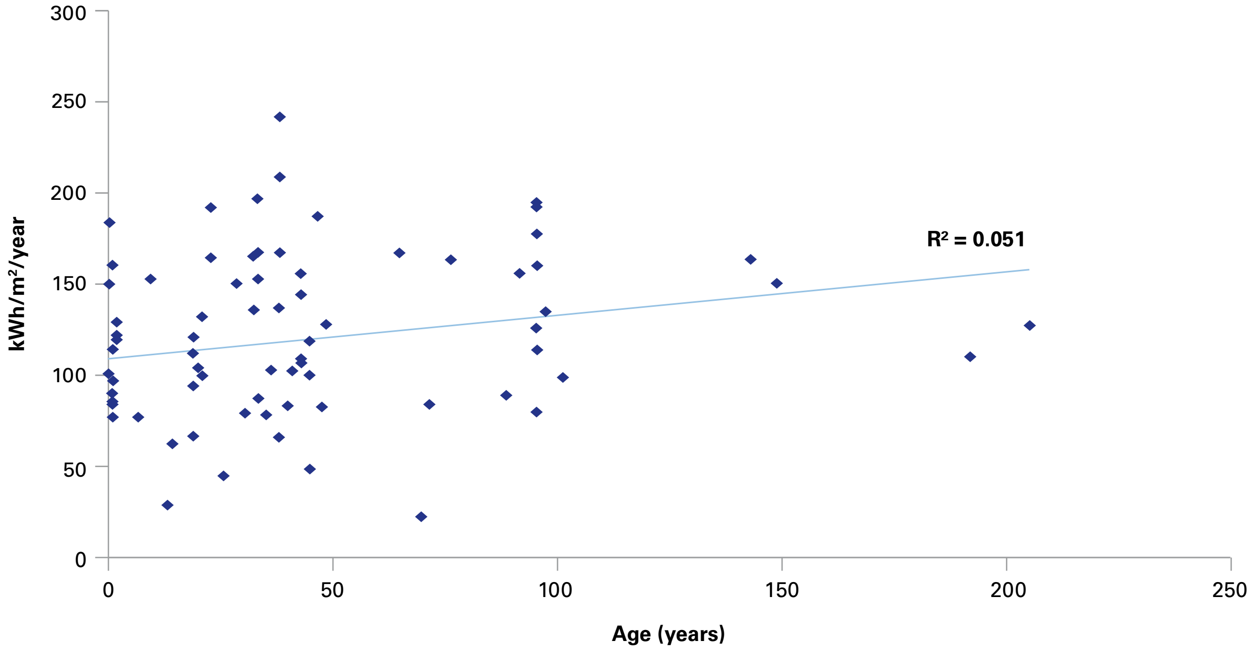



*Figure 4.9* *Age of houses in field trial versus space heating demand (kWh/m²/year)*



Although the correlations are weak and there is considerable variation in annual heat demand within each group of houses – suggesting wide variation in the thermal performance of superficially similar houses and variations in occupier behaviours – larger houses, which are typically detached and have more bedrooms, generally have the highest heat demands.

Note that there is virtually no correlation between the age of the houses in the field trial and their space heating demand on a per m$^2$ basis, as shown in *Figure 4.9*. However, the houses built in the last few years do appear to have somewhat lower space heating requirements than the overall average.

Stirling engine micro-CHP systems are more likely to save carbon relative to a condensing boiler in households with higher heat demands. Micro-CHP installers should therefore take care to estimate the annual heat demand of a household on a case-by-case basis although larger, detached houses with more than three bedrooms are likely to be an attractive initial market.

It is also important that incentive schemes designed to encourage the roll-out of micro-CHP systems should ensure that they are installed correctly to maximise the carbon savings achieved. The Microgeneration Certification Scheme (MCS) includes standards for micro-CHP products and how they are installed and is used to determine whether systems qualify for Feed-in Tariffs. In particular, the scheme requires that "the Contractor shall provide evidence that the micro-generation package selected is of appropriate output for the building, (and hot water system if applicable), and that the design of the heat distribution systems and controls is compatible with efficient operation of the package."[13]

## The importance of installation and control

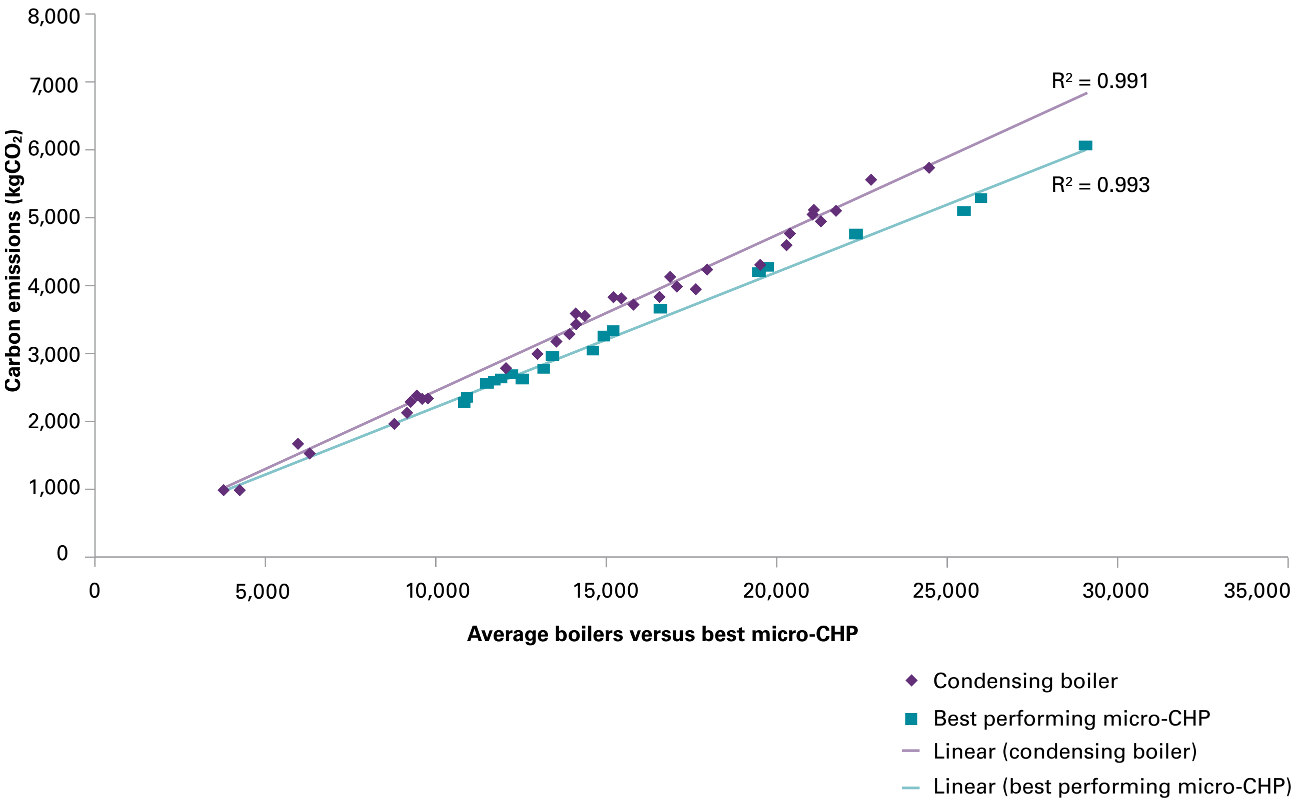
Even taking into account the differences in annual heat demand between households, there remains considerable variation in the performance of micro-CHP systems. There can be a variation of up to 15% between the carbon benefits ratios of two sites with similar heat demands and the same micro-CHP system.

Some of the specific drivers for this variation in performance were discussed in the Interim Report. However, for the purposes of deriving general conclusions about the carbon savings that could be achieved by deploying micro-CHP, it is useful to assume that the remaining variation is potentially controllable. That is to say that by ensuring proper installation and control of domestic micro-CHP systems, it may be possible to ensure that all installed systems perform close to the level achieved by the best-performing systems in the field trial. It could be argued that such an improvement is less likely to be readily achievable for condensing boilers, as the technology and its supply chain are considerably more mature. Although this assessment is not a robust approach on its own, it does provide an illustration of the possible carbon savings that might be achieved by optimising the installation and operation of domestic micro-CHP systems.

To make an approximate estimate of this potential, *Figure 4.10* compares the annual carbon emissions of all the condensing boiler sites in the field trial with the best performing third of the micro-CHP sites. The trend lines show that the carbon savings achieved are significantly greater than when comparing the full samples.

[13] MIS 3007 issue 2 (available from www.microgenerationcertification.org).

*__Figure 4.10__ Average boilers versus best micro-CHP*




Again, comparing the carbon intensity of heat supplied in the two samples gives an estimate of the aggregate carbon saving – around 10%.

A statistical comparison of these two samples suggests that the mean carbon saving in an individual household is also likely to be around 10%, with a likely range of between 6% and 15%. For a 'typical' large house with an annual heat demand of around 20,000kWh, the absolute carbon saving would therefore be between 300kg and 700kg, with a mean of around 500kg. Note that in this case only 19 micro-CHP sites are included in the sample, so the results should be treated with some caution.

The carbon saving achieved by installing domestic micro-CHP systems could be significantly increased by optimising their installation and operation.

## Small commercial heating systems

As the field trial did not include small commercial condensing boilers, only a much simpler comparison is possible between the performance of micro-CHP systems in the field trial with the theoretical performance of an equivalent condensing boiler.

Also, as there were only a small number of small commercial micro-CHP systems in the field trial for which a full year of annual data was available, and as shown previously, there is very little seasonal variation in the performance of small commercial systems, the following analysis is based on the monthly performance data.

The distribution of monthly CBR shown previously in *Figure 3.12* can be compared with a theoretical value for condensing boilers (89.4%) based on the typical performance seen during the field trial (i.e. a thermal efficiency of 85.5% and an electrical efficiency of -1.5%). Small commercial condensing boilers are assumed to have no greater variation in performance than was observed for the domestic systems. It is then clear that the small commercial micro-CHP systems consistently outperform condensing boilers in terms of carbon emissions and significant carbon savings can be achieved in these applications.

***Figure 4.11*** *Monthly carbon emissions against heat supplied by micro-CHP system*

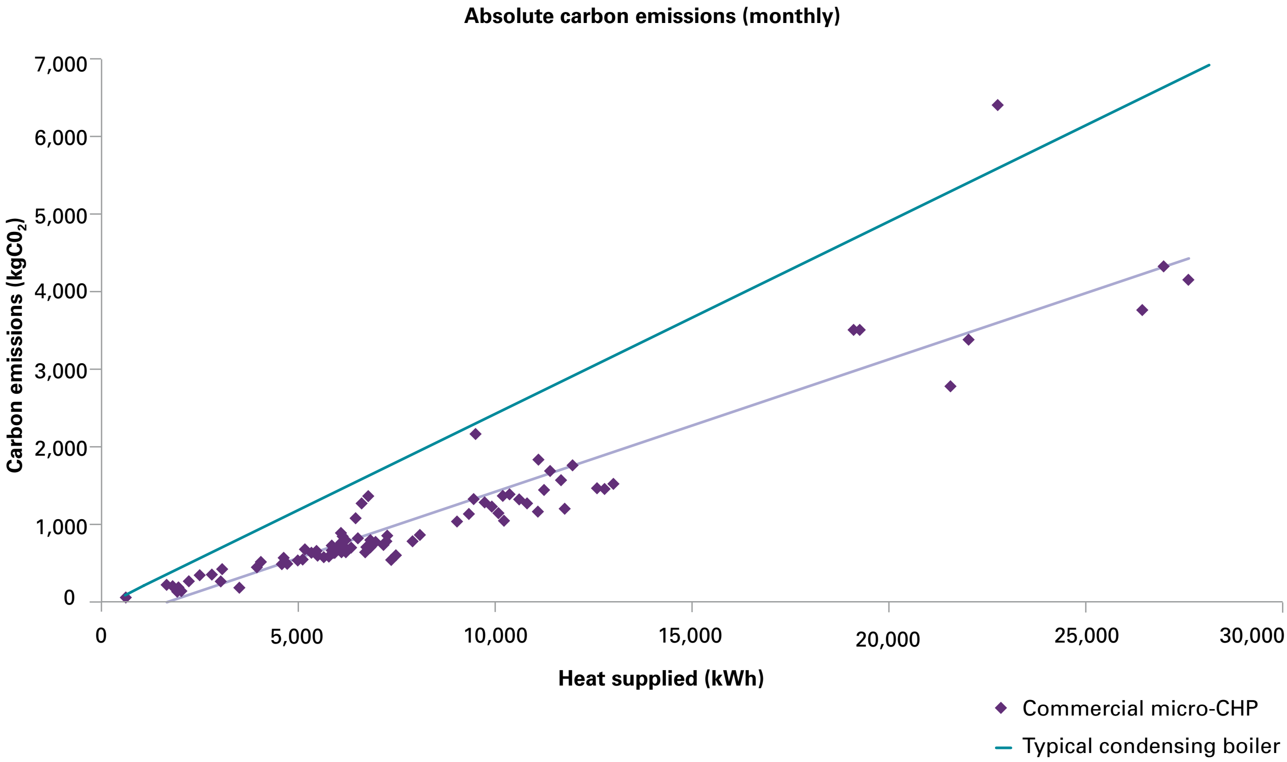



***Figure 4.12***

| | 'Typical' condensing boiler (theoretical) | Micro-CHP (average of all sites from field trial) | |
|---|---|---|---|
| Thermal efficiency | 85.5% | 52.0% | |
| Electrical efficiency | -1.5% | 22.3% | |
| Gas used per kWh heat supplied | 1.170kWh | 1.923kWh | |
| Electricity generated per kWh heat supplied | -0.018kWh | 0.429kWh | Difference |
| Carbon emissions per kWh heat supplied | 0.237kg$CO_2$ | 0.129kg$CO_2$ | -45% |

*Figure 4.11* shows the absolute monthly carbon emissions for small commercial sites in the field trial and a theoretical 'typical' condensing boiler against the monthly heat supplied by the micro-CHP system at each site.

As expected, the small commercial micro-CHP systems deliver significant carbon savings relative to condensing boilers; the absolute savings increase at higher heat demands. The percentage saving is estimated from the thermal and electrical efficiencies of the systems in the field trial, as illustrated in *Figure 4.12*.

The mean carbon intensity of heat supplied by the micro-CHP systems is estimated to be around 45% lower than for a condensing boiler with a likely range of 33% to 57%.

However, the small commercial micro-CHP systems in the field trial were typically installed as one of several boilers in a plant room, supplying only a small proportion of the overall heat demand. They were typically configured as the lead boiler to ensure long running hours and efficient operation.

In a 'typical' small commercial application, a micro-CHP system might operate for ~6,000 hours per year (i.e. at a capacity factor of around 68%). Although the micro-CHP system might only represent less than 10% of the total rated thermal output of the heating system, it would provide around 36% of the total heat supplied due to its longer running hours.

In this case, the net saving would be around 16% of the total carbon emissions from the plant room, with a likely range of between 12% and 21%. For a 'typical' application in which the total heat supplied was around 400MWh per year (say a medium-sized office building with a floor area of several thousand square metres) this would equate to an absolute annual carbon saving of around 15t$CO_2$.

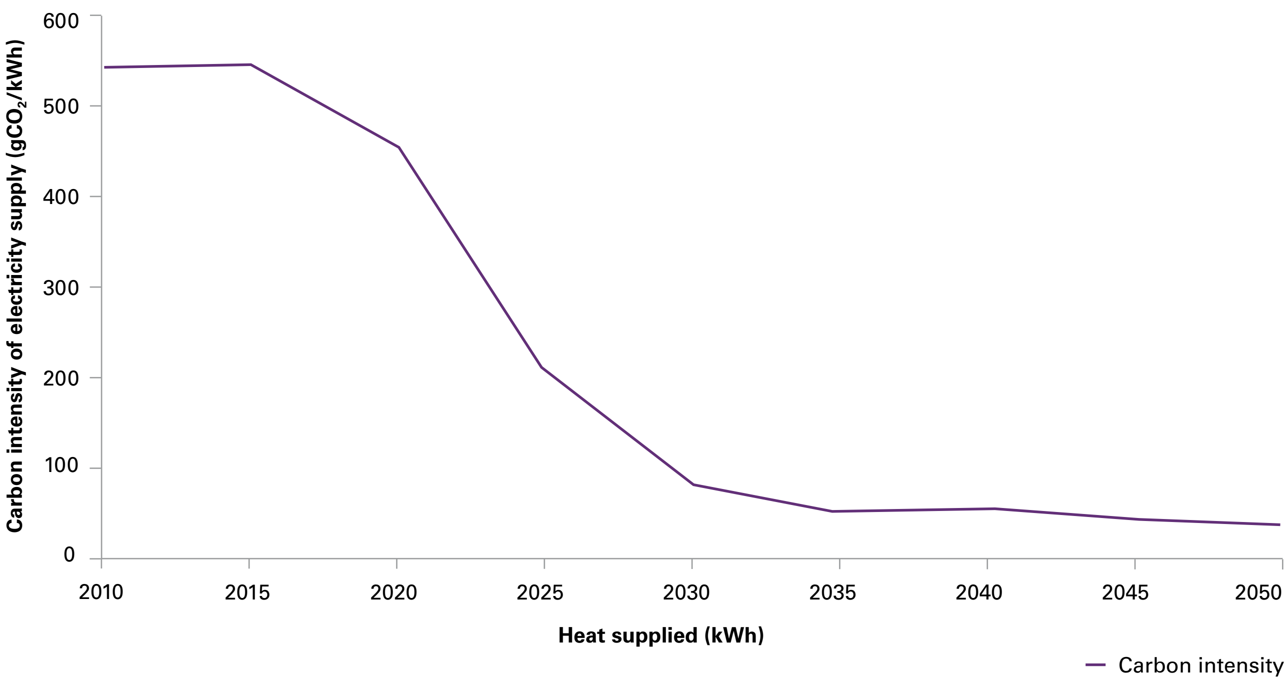
## Sensitivity to grid carbon intensity

The carbon benefit of substituting a gas-fired condensing boiler with a gas-engine micro-CHP system results from the electricity generated by the micro-CHP. This displaces electricity that would otherwise have been generated by central power stations and supplied through the national grid. As a result, the net carbon benefit is strongly dependent on the carbon intensity of the grid electricity being displaced.

In the UK, the government is committed to making dramatic cuts in carbon emissions across the economy over the next 40 years and rapid decarbonisation of grid electricity is likely to be essential to achieving this. As more low carbon electricity generating capacity (such as renewable energy, nuclear power or fossil fuelled power stations with carbon capture and storage) is installed over the coming years, the carbon benefit of micro-CHP relative to alternative heating systems will fall in the UK.

*Figure 4.12* shows a possible scenario for the reduction of the carbon intensity of grid electricity from the Committee on Climate Change's recent progress report[14]. Rapid deployment of low carbon capacity over the next 20 years results in a reduction of the carbon intensity of grid electricity from the recent level of around 0.5kg$CO_2$/kWh to less than 0.1kg$CO_2$/kWh by 2030.

***Figure 4.13*** *Projected carbon intensity of UK grid electricity (Committee of Climate Change)*




[14] Meeting Carbon Benefits – ensuring a low carbon economy (available from www.theccc.org.uk, June 2010).

In this scenario, the carbon intensity of grid electricity is likely to change significantly over the lifetime of a typical micro-CHP system installed in the next few years. It may therefore be more useful to consider the average grid carbon intensity looking over a period several years into the future to estimate the benefits of micro-CHP.

The analysis in the previous section used a standard value for the carbon intensity of grid electricity of 0.568kg$CO_2$/kWh, representative of the situation today. However, using a lower value of grid electricity of 0.43kg$CO_2$/kWh, which may be more representative of the carbon intensity of grid electricity by around 2020, lower carbon savings would be predicted[15].

- Within the estimated uncertainty there would be no significant difference between the aggregate carbon emissions of the domestic condensing boilers and micro-CHP systems in the field trial.
- For households where the annual heat demand was greater than 15,000kWh, the estimate for the mean saving for an individual household would be reduced to 2% (from 9%).
- Comparing the performance of all condensing boilers in the trial with the best-performing micro-CHP systems, the mean saving for an individual household would be around 4%.
- For a 'typical' application of a small commercial micro-CHP system the overall carbon saving would be reduced from 16% to around 8%.

This simple analysis suggests that there is a limited 'window of opportunity' during which the current generation of micro-CHP systems, based on Stirling engines, could achieve significant carbon savings in the UK. If the grid is substantially decarbonised during the lifetime of a system, the carbon savings may be negligible or even negative. In the worst case, this window of opportunity could therefore be limited to the next five to 10 years, even if the performance of these micro-CHP systems can be incrementally improved.

However, if deployment of low carbon generating capacity proceeds more slowly than anticipated by the CCC, then the window of opportunity in the UK could be significantly longer; perhaps 15-20 years if the grid is not substantively decarbonised until 2040.

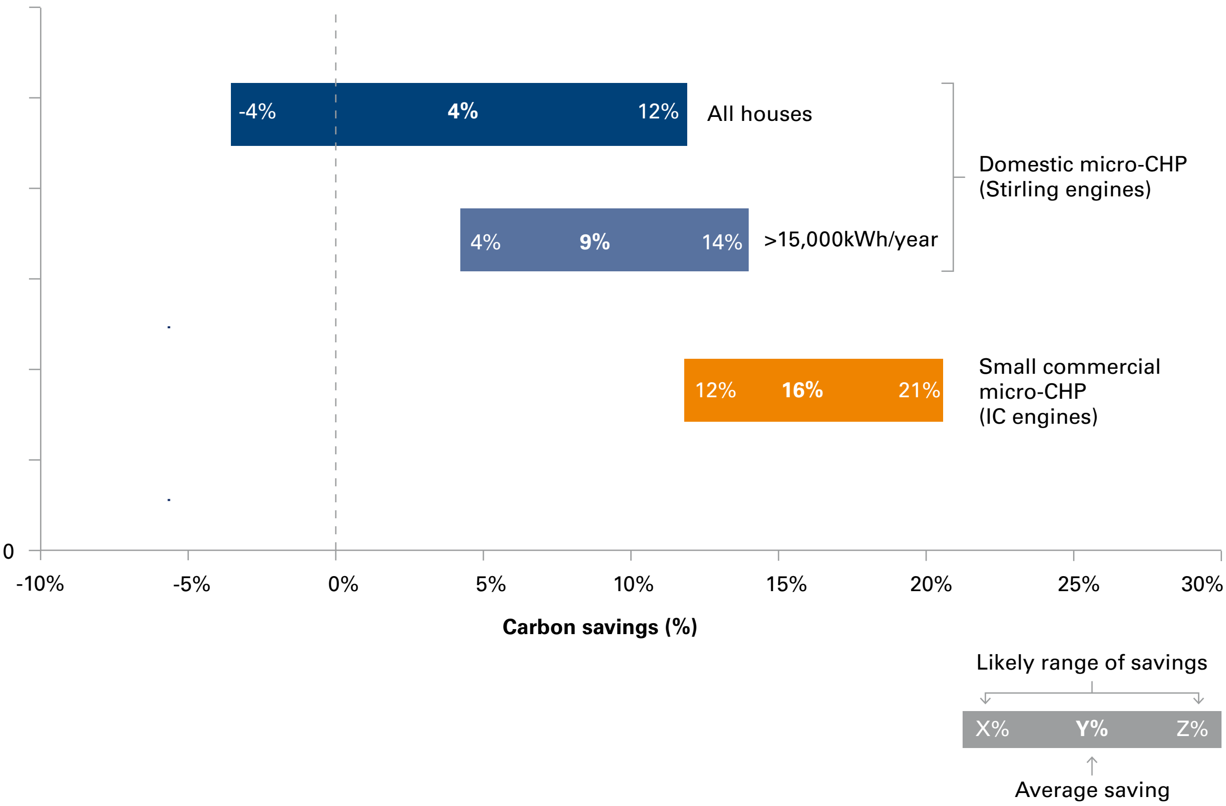
The carbon intensity of grid electricity is also significantly higher in some other major economies, and is likely to remain so for a significant period, particularly in newly industrialised countries which are likely to remain more reliant on fossil fuels. In China, the average carbon intensity of grid electricity between 2006 and 2008 was 0.764kg$CO_2$/kWh[16]. This may suggest that in the long term, where sufficient incentives to reduce carbon emissions emerge in these economies, they may be more attractive for micro-CHP developers than the UK.

It should be noted that future generations of micro-CHP systems based on fuel cells, which are expected to generate a much higher ratio of electricity to heat, will achieve significant carbon savings even for much lower values of the carbon intensity of grid electricity. They are therefore likely to have a longer window of opportunity in the UK than systems based on Stirling engines. Further analysis would be required to fully understand the potential role for fuel cell micro-CHP in a low carbon energy system in the UK.

[15] These values are also consistent with those used in the Interim Report.

[16] $CO_2$ Emissions From Fuel Combustion Highlights (2010 Edition), IEA.

***Figure E1*** *Summary of percentage annual savings for individual sites in the field trial*




## Summary

*Figure 4.13* shows a summary of the mean and likely range of carbon savings for the domestic and small commercial micro-CHP systems in the field trial.

Stirling engine micro-CHP systems could make a significant contribution to reducing carbon emissions in the UK as they are commercialised over the next few years, particularly if they are targeted at suitable buildings with high and consistent heat demands. However, there is a limited window of opportunity to make carbon savings created by the planned decarbonisation of grid electricity. In the long term, this technology may therefore have a more significant impact on carbon emissions in economies that are likely to remain more dependent on fossil fuels for electricity generation.

# 5. Economics of micro-CHP

The Micro-CHP Accelerator has provided an independent set of data on real world performance of the technology in domestic and small commercial applications in the UK. These data are used in the following sections as the basis of assessments of the economic potential of the technology – both for individual applications and at the national level.

## Electricity export to the grid

Where the electricity generated by a micro-CHP system is used within the building it offsets the need to purchase electricity from the grid, while the user may receive a different level of compensation for electricity exported to the local network. The overall proportion of electricity exported over the whole year is therefore an important factor in the overall economics of micro-CHP installations.

All of the micro-CHP systems in the field trial were designed to follow the demand from the space heating and domestic hot water systems in the building. Electricity generated by the micro-CHP system is used in the building as long as the instantaneous load from electrical appliances in the building happens to be less than the electrical output of the micro-CHP. Any excess is exported to the local electricity network. Electricity is imported from the grid as normal while the electrical load in the building is greater than the output of the micro-CHP.

The electricity demand in a household varies depending on the weather conditions, season, day of the week, time of day, and also on a second-by-second basis depending on the specific appliances in operation. The typical range observed in the field trial was from less than 50W to several kW.

The high resolution of the electricity demand data collected in the field trial (every five minutes) has enabled the relationship between heat and electricity generation and export to be analysed in detail. It was shown in the Interim Report that a significant proportion of the electricity generated can be exported even during periods of high average electricity demand (for example winter evenings), due to second-by-second differences between the instantaneous electricity demand from household appliances and the output of the micro-CHP system.

*Figure 5.1* shows the distribution of the annual electricity exported from each of the domestic micro-CHP sites. Although the mean proportion of electricity generated that was exported was around 65%, there was a very wide range. One site exported only 17%, while others exported over 90%.

*Figure 5.1* Proportion of electricity generated that is exported over the year

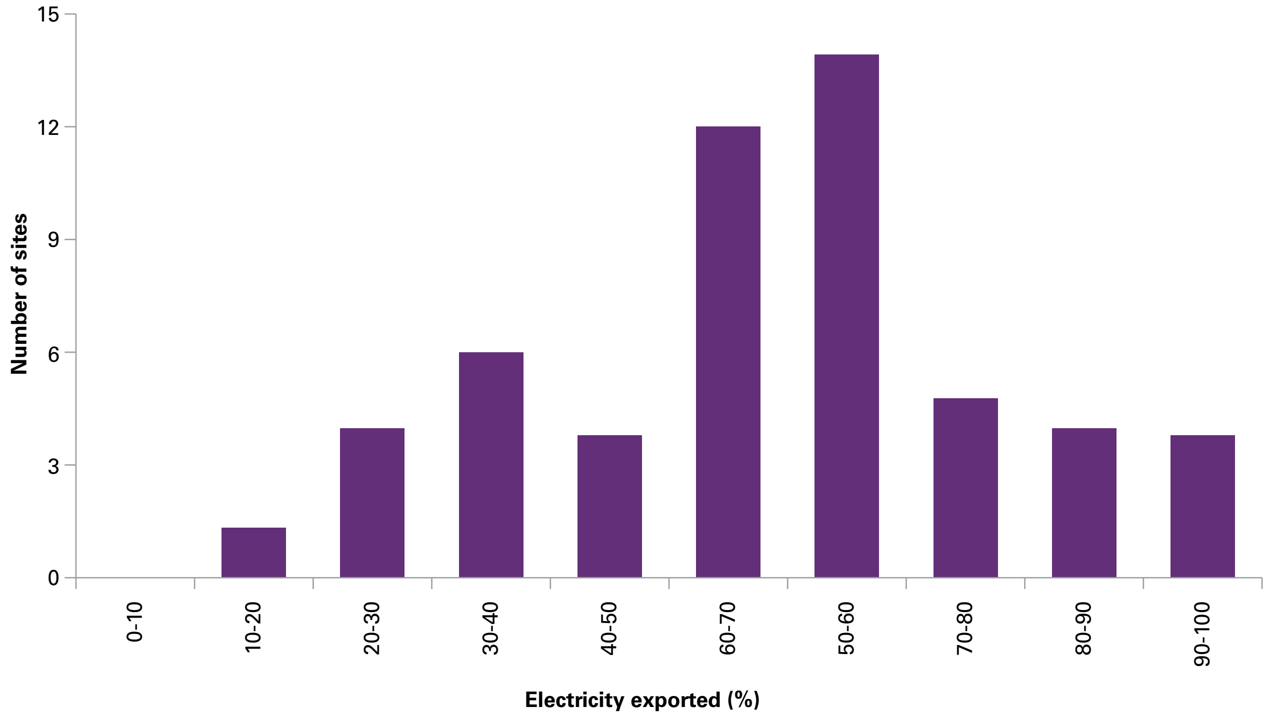
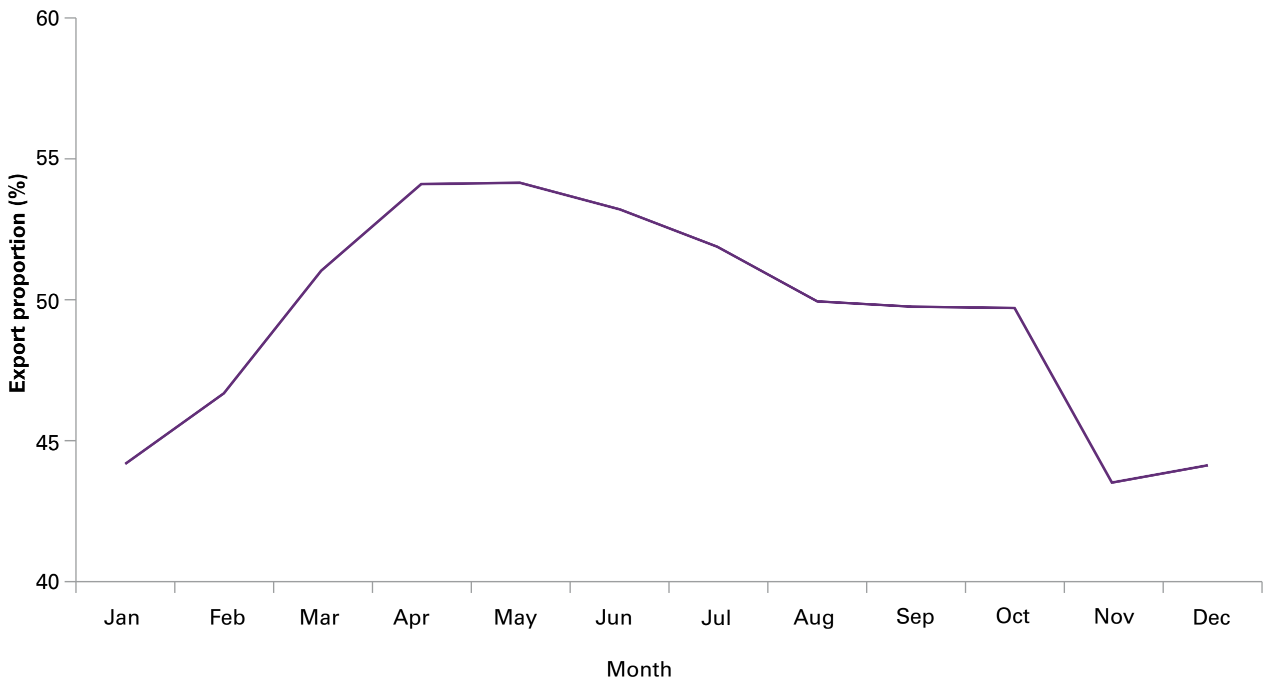



*Figure 5.2* Seasonal variation in proportion of total electricity generated that was exported



The proportion of electricity exported shows a strong dependence on the seasons, as shown in *Figure 5.2*. The proportion exported is significantly higher during the summer months due to the dominance of domestic hot water demand, which was observed to be very sporadic and therefore weakly correlated with electricity demand. The winter months are more significant to the annual proportion, as over 80% of the annual electrical output of the micro-CHP systems was typically generated between October and March.

For the commercial micro-CHP sites in the trial the average proportion of electricity exported was much lower – typically less than 3% – as the electrical output was sized to be less than the electrical base load of the building. There was no significant seasonal variation.

The impact of electricity exported from large numbers of micro-CHP devices distributed throughout the electricity network is discussed in the Interim Report.

## The economics of micro-CHP

In this section, the measured performance of the micro-CHP systems in the field trial is used to develop a simple model of the economics of domestic and small commercial applications.

Indications from micro-CHP manufacturers suggest that the price of an installed micro-CHP system will typically be significantly higher than that of an equivalent condensing boiler. The economic case for micro-CHP systems will depend on whether the net benefit of the electricity generated is sufficient to offset this additional capital cost.

### Subsidies

The results of the field trial have demonstrated that by generating electricity, much of which is exported, micro-CHP systems can achieve significant reductions in carbon emissions when compared to an equivalent condensing boiler, but the systems must be installed in appropriate applications and be set up and operated correctly to achieve significant carbon savings.

The initial costs of micro-CHP systems are likely to be high, but are expected to fall if manufacturers can achieve economies of scale through volume production.

To overcome this initial hurdle, the Government has therefore included micro-CHP technologies in the system of Feed-in Tariffs (FITs), which is designed to encourage the widespread uptake of a range of micro-generation technologies. The scheme guarantees to pay a fixed tariff for each kWh of electricity generated, and an additional payment for each kWh of electricity exported to the grid. It is designed to increase the number of installations of micro-generation technologies by ensuring that consumers receive an attractive financial return on their investment of between 5% and 8%, equivalent to a simple payback period of between 12 and 10 years.

As it is a relatively new technology, with limited experience of market volumes and retail prices in the UK, micro-CHP has been included in the scheme on a trial basis for the first 30,000 units sold. The generation tariff has initially been set at 10p/kWh, while the export tariff is 3p/kWh. The scheme currently only applies to micro-CHP systems with electrical output less than 2kW – mostly units suitable for domestic applications[17].

The analysis that follows explores the likely impact of these tariffs on the economics of micro-CHP.

### Modelling the economics of domestic micro-CHP

*Figure 5.3* shows the key assumptions and outputs of a simple model comparing the economics of a domestic micro-CHP system installed in a large house with an annual heat demand of 20,000kWh with an equivalent condensing boiler.

The electrical and thermal efficiencies are based on the average annual values measured in the field trial. The installed cost of the micro-CHP system is assumed to be around £5,000, consistent with the retail price of Stirling engine micro-CHP systems recently launched on the UK market. This is compared to the typical installed cost of a large condensing boiler of around £2,500. The installation and maintenance costs are assumed to be the same for the micro-CHP unit and condensing boiler.

[17] http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/renewable/feedin_tariff/feedin_tariff.aspx

***Figure 5.3** Economics of domestic micro-CHP*

| **Market assumptions** | |
|---|---|
| Cost of gas* (p/kWh) | 4.0 |
| Cost of electricity* (p/kWh) | 14.0 |
| Generation tariff (p/kWh) | 10.0 |
| Export tariff (p/kWh) | 3.0 |
| Micro-CHP retail price (installed) | £5,000 |
| Gas boiler retail price (installed)** | £2,500 |
| **Performance assumptions (based on field trial results)** | |
| Electrical efficiency | 6% |
| Thermal efficiency | 71% |
| Total efficiency | 77% |
| Proportion of electricity exported | 60% |
| Gas boiler efficiency | 85% |
| Gas boiler electricity consumption | 1.5% |
| **Model results** | |
| Annual heat demand (kWh) | 20,000 |
| Electricity generated (kWh) | 1,690 |
| Additional gas used (£) | £185 |
| Electricity import avoided (£) | £144 |
| Electricity export reward (%) | £30 |
| Generation reward | £169 |
| Net annual saving | £158 |
| Payback | 15.8 years |

* Based on average UK domestic retail electricity and gas bills for 2009 (Source: DECC).

The model shows that in meeting an annual heat demand of 20,000kWh, the micro-CHP unit would also generate around 1,690kWh of electricity. The cost of the gas used would be higher than for the condensing boiler for the same amount of heat supplied. In this example the household's annual gas bill would increase by around £185. The electricity generated and used in the house reduces the need to purchase grid electricity and is valued at the retail price of electricity. In this example, the avoided cost of imported electricity is around £144, which is significantly less than the cost of the additional gas used.

This highlights that based on current prices, a Stirling engine micro-CHP unit could actually be more expensive to run than a condensing boiler in the absence of a reward for electricity exported or other subsidy.

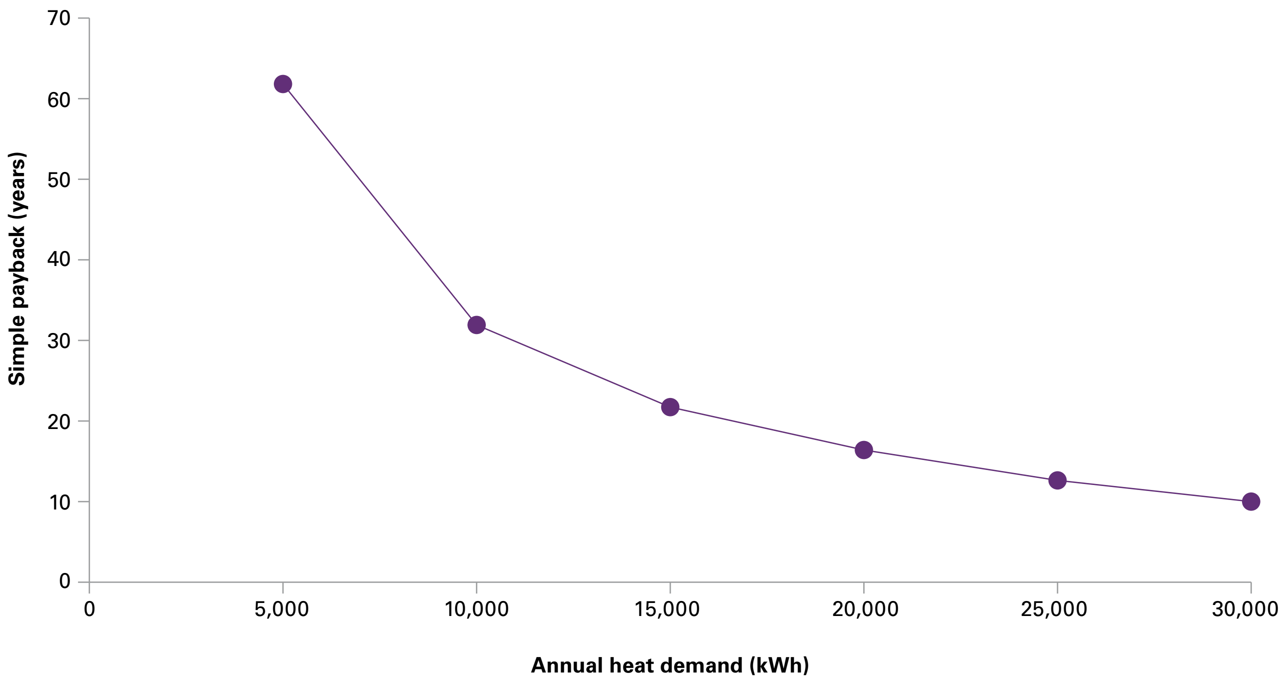
However, taking into account the subsidy currently provided by the FITs, the value of the electricity generated and exported is enhanced, which improves the economics of domestic micro-CHP. In this example the generation tariff of 10p/kWh provides the householder with an additional income of £169 per year, and the export tariff of 3p/kWh provides a further £30 a year.

The net saving to the householder is £158 a year, which results in a simple payback period of just less than 16 years, or an IRR of around 2.4% for this particular example.

## The importance of annual heat demand

As the economics of a micro-CHP system are strongly driven by the value of the electricity generated, the cost effectiveness improves significantly in households with higher heat demands as more electricity is also generated. *Figure 5.3* shows the dependence of the simple payback period on the annual heat demand of the household, otherwise using the same assumptions made in *Figure 5.3*. The value of the greater amount of electricity generated offsets the (fixed) capital cost more quickly for higher heat demands.

***Figure 5.4*** *Simple payback versus annual heat demand (including FITs)*




Uptake of micro-CHP can therefore be expected to be initially limited to larger households with higher heat demands. This is consistent with the finding of this field trial that micro-CHP systems are more likely to achieve a significant carbon saving in these applications. Indeed, below 15,000kWh (the threshold below which no significant carbon savings were observed) the payback period is likely to be greater than the lifetime of a typical heating system. Consumers are unlikely to find this an attractive investment.

## Potential improvements

The analysis above is based on the performance of the micro-CHP units featured in the field trial. Developers continue to invest in improving the performance of their systems and reducing the costs. Evidence from previous research into consumers' attitudes suggests that most are unwilling to make an investment in micro-generation unless the payback period is less than around five years[18].

*Figure 5.5* shows the effect of applying these improvements sequentially for a typical installation in a large house with annual heat demand of 20,000kWh, including generation and export tariffs.

### Minimising export

As the export tariff is much less than the retail price of electricity, a householder may be able to improve the economics of a micro-CHP system by maximising the proportion of the electricity generated that is used in the house rather than exported. This could be achieved by, for example, scheduling electrical loads such as a washing machine to coincide with periods of heat demand. However, the effect is relatively small. For the case described above, reducing the proportion of electricity that is exported to 50% would reduce the payback period from 16 to 14 years, increasing the IRR to 3.6%.

### Improving electrical efficiency

Increasing the electrical efficiency of micro-CHP systems would significantly improve their economics, as the value of a unit of electricity generated is much higher than a unit of heat[19]. Increasing the electrical efficiency from 6% to 9% (for the same overall efficiency) would reduce the payback period to just less than seven years.

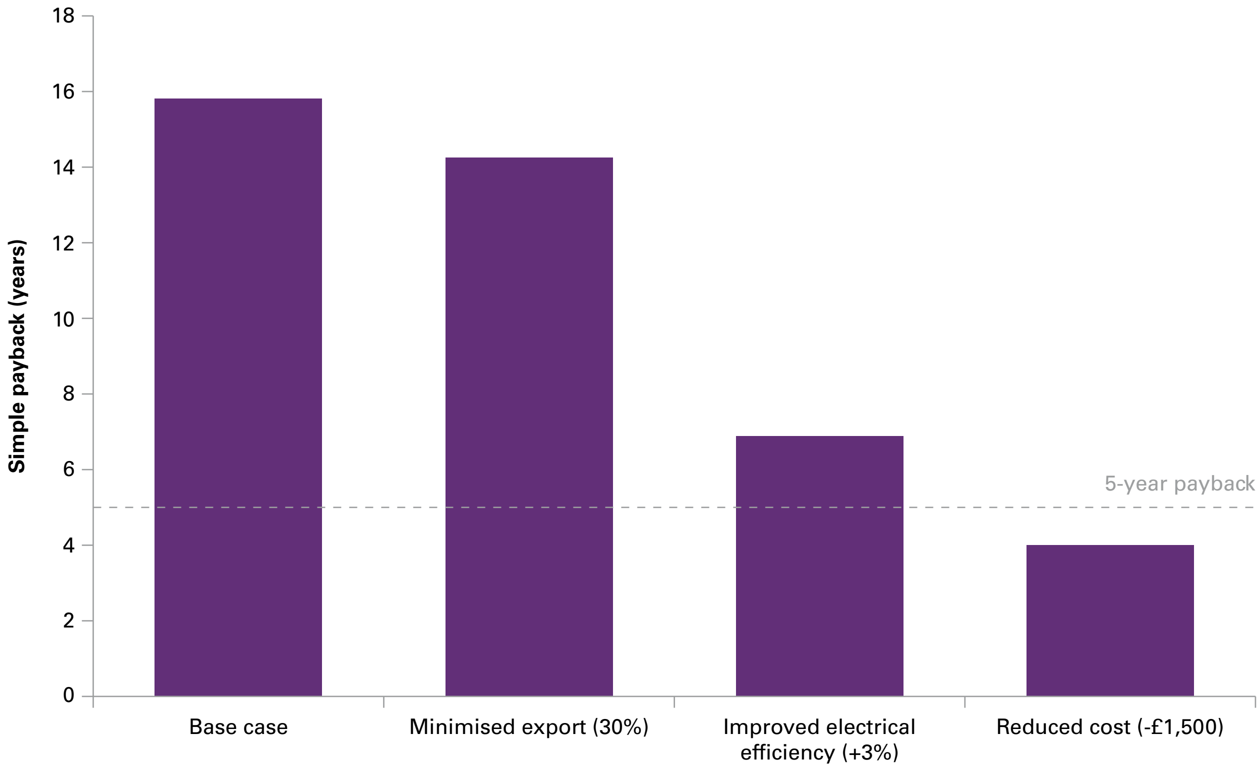
### Reduced capital cost

The difference in capital cost between a micro-CHP system and an equivalent condensing boiler is one of the key drivers of its cost effectiveness. If the difference in cost could be reduced to £1,500 in addition to the performance improvements described above, the payback period would be reduced to just over four years.

[18] The growth potential for Microgeneration in England, Wales and Scotland, element energy, June 2000 (available from www.berr.gov.uk/files/file46003.pdf)

[19] Note that this range may be conservative. We understand that higher electrical efficiencies have been achieved in laboratory test conditions for a Stirling engine micro-CHP system now available commercially in the UK.

***Figure 5.5*** *Impact of improved performance and reduced cost on cost-effectiveness of domestic micro-CHP (with current UK subsidy regime)*




## Economics of small commercial micro-CHP

The economics of a typical installation of small-commercial micro-CHP are modelled in *Figure 5.6*. Two examples are given, for micro-CHP units with electrical output of 5kW and 13kW respectively. Both units are assumed to operate as lead boilers and to run for approximately 6,000 hours per year (i.e. a capacity factor of around 68%), which is similar to the run hours observed in the field trial. Thermal and electrical efficiency figures are based on the results of the field trial. Costs are indicative and are assumed to be inclusive of installation and commissioning. Indicative prices for gas and electricity are used, which are significantly lower than domestic tariffs. Note though that commercial contracts for gas and electricity vary widely as they are negotiated independently.

It is assumed that if a micro-CHP unit is added to a plant the installed capacity or cost of the condensing boilers will not be reduced. This practice ensures that the plant room has sufficient capacity should the micro-CHP unit break down, and is understood to be common in the industry.

***Figure 5.6*** *Economics of small, commercial micro-CHP*

| **Market assumptions** | | |
|---|---|---|
| Cost of gas (p/kWh) | 3.0 | |
| Cost of electricity (p/kWh) | 8.0 | |
| Generation tariff* (p/kWh) | 0.0 | |
| Export tariff (p/kWh) | 0.0 | |
| | **5kWe** | **13kWe** |
| Micro-CHP price (installed) | £17,000 | £50,000 |
| **Performance assumptions (based on field trial results)** | | |
| Electrical efficiency | 22.3% | |
| Thermal efficiency | 52.0% | |
| Total efficiency | 74.3% | |
| Proportion of electricity exported | 3% | |
| Gas boiler thermal efficiency | 85.5% | |
| Gas boiler electricity consumption | -1.5% | |
| **Model results** | | |
| Annual heat supplied (kWh) | 69,955 | 181,883 |
| Electricity generated (kWh) | 30,000 | 78,000 |
| Additional gas used (£) | £1,581 | £4,111 |
| Electricity import avoided (£) | £2,426 | £6,308 |
| Electricity export reward (%) | N/A | N/A |
| Generation reward | N/A | N/A |
| Net annual saving | £845 | £2,197 |
| Payback | 20.1 years | 22.8 years |

* The FIT is currently limited to micro-CHP systems with electrical output <2kW.

For the 5kWe unit, the micro-CHP system is estimated to generate around 30MWh of electricity in supplying around 70MWh of heat. The net cost saving of around £850 a year is not sufficient to achieve an attractive financial return, given the installed cost of around £17,000. The simple payback, with no subsidy, is estimated to be around 20 years.

Similarly, the larger unit is estimated to provide around 180MWh of heat per year and generate around 78MWh of electricity. The net annual cost saving in this case is estimated to be around £2,200, resulting in a similar payback period of around 23 years.

The small commercial micro-CHP systems in the field trial were relatively mature products based on well-proven IC-engine technology. There may therefore be less potential to improve performance and reduce costs than for the domestic Stirling engine systems.

However, it was shown in Section 4 that IC-engine micro-CHP systems can achieve significant carbon savings in small commercial applications due to their high power:heat ratios. There may therefore be a case for offering generation and export tariff subsidies to these systems. For the examples above, a moderate generation tariff of 3p/kWh would improve the IRR to around 6-8%, which may be sufficient to encourage further implementation of this technology.

## Summary

- The domestic Stirling engine micro-CHP systems in the field trial typically exported around 50-70% of the electricity they generated over a year. The small commercial IC-engine systems typically exported only a small fraction of the electricity they generated.
- The current generation tariff of 10p/kWh would not be sufficient to achieve an attractive payback period for domestic micro-CHP systems based on the estimated costs and performance of the models featured in the field trial.
- However, manufacturers may be able to improve performance and reduce the costs, in which case attractive returns could be achieved, particularly for larger houses with higher heat demands.
- It is estimated that IC-engine micro-CHP systems have a simple payback of around 20 years in small commercial applications, which is unlikely to be attractive.
- However, a moderate generation tariff of 3p/kWh may be sufficient to encourage further implementation of small commercial micro-CHP.

# 6. Market potential

The results of the field trial have demonstrated that significant carbon savings can be realised by installing micro-CHP in individual applications. For optimum savings, installations should be targeted to houses with high, consistent heat demand, performance continues to improve and installation and controls can be optimised.

In this section, initial estimates are presented for the 'technical potential' of micro-CHP to reduce carbon emissions in appropriate domestic and small commercial applications. The 'economic potential', taking into account other constraints such as consumer response to cost, pricing or policy instruments or preference for alternative heating technologies, has not been estimated here[20].

## Domestic applications

### Market size

Domestic properties are responsible for around 35% of the UK's carbon emissions. In 2005 there were around 21.5 million gas-connected households in the UK, with an overall average annual household gas consumption of around 19,000 kWh. *Figure 6.1* shows an estimated distribution of households by their annual heat demand, derived from geographical data on annual gas use, 2001 census data on household sizes and estimated average efficiency of heating systems[21].

It can be seen that there is an estimated market of around 8 million homes in the UK with annual heat demands above 14,000kWh, which may potentially be suitable for models of micro-CHP similar to those featured in the field trial.

The gas used for heating and hot water in these households is around 200TWh a year, leading to carbon emissions of around 40Mt$CO_2$/year.

A very approximate estimate of the overall carbon saving potential of micro-CHP in this market is given by applying the percentage saving seen in the field trial for houses with higher heat demands to this figure. This would imply that almost 4 million tonnes a year could be saved if micro-CHP were installed in all suitable households in the UK.

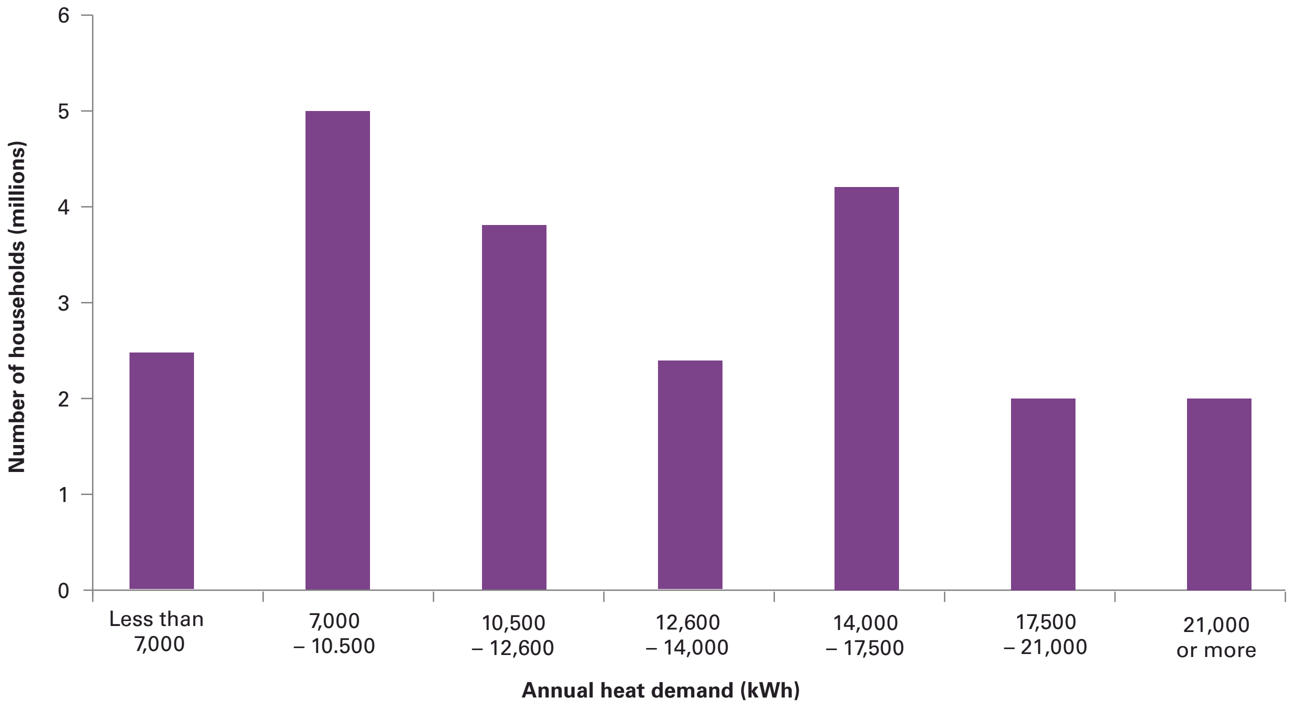
Of an estimated 1.5 million boilers sold annually in the UK, around 30% are standard condensing boilers (i.e. not 'combi-boilers'), which could potentially be replaced by micro-CHP units similar to those in the field trial. Assuming that boiler sales are distributed proportionately across households of different sizes, annual sales in suitable houses would be around 170,000.

In practice, both these estimates provide upper bounds for the market potential of current models of micro-CHP. Uptake will be constrained by considerations such as physical space, increased disruption during installation, the cost of micro-CHP compared with alternative heating systems and landlord/tenant issues.

[20] A number of studies have investigated the economic potential of micro-generation technologies, e.g. Element Energy's The Growth Potential for Microgeneration in England, Wales and Scotland (www.berr.gov.uk/files/file46003.pdf).

[21] Gas Demand and Micro-CHP: a report on potential UK market size and distribution, University College London. Heating system efficiency taken from data given by BRE for average overall heating system efficiency in 2004 of 71.7% (Utley & Shorrock, 2006).

*Figure 6.1* *Distribution of UK households by annual heat demand*




## Geographical distribution

The geographical distribution of average annual gas demand is plotted in *Figure 6.2*. Areas with a higher average annual heat demand are shown in darker shades. Information about the density of gas connections in each region is overlaid onto this plot, in order to highlight areas that are likely to have more gas-connected households with high heat demands – potentially attractive markets for micro-CHP developers.

It can be seen that, in general, urban areas tend to have the highest concentration of houses connected to the gas grid. *Figure 6.3* shows the detailed distribution for Greater London, where it is evident that gas-connected houses with higher heat demands are concentrated in the suburban ring around the city centre. This is therefore likely to be an attractive area to focus attention for the early market introduction of micro-CHP systems.

*__Figure 6.2__ National gas demand map based on gas grid connection density and gas consumption*

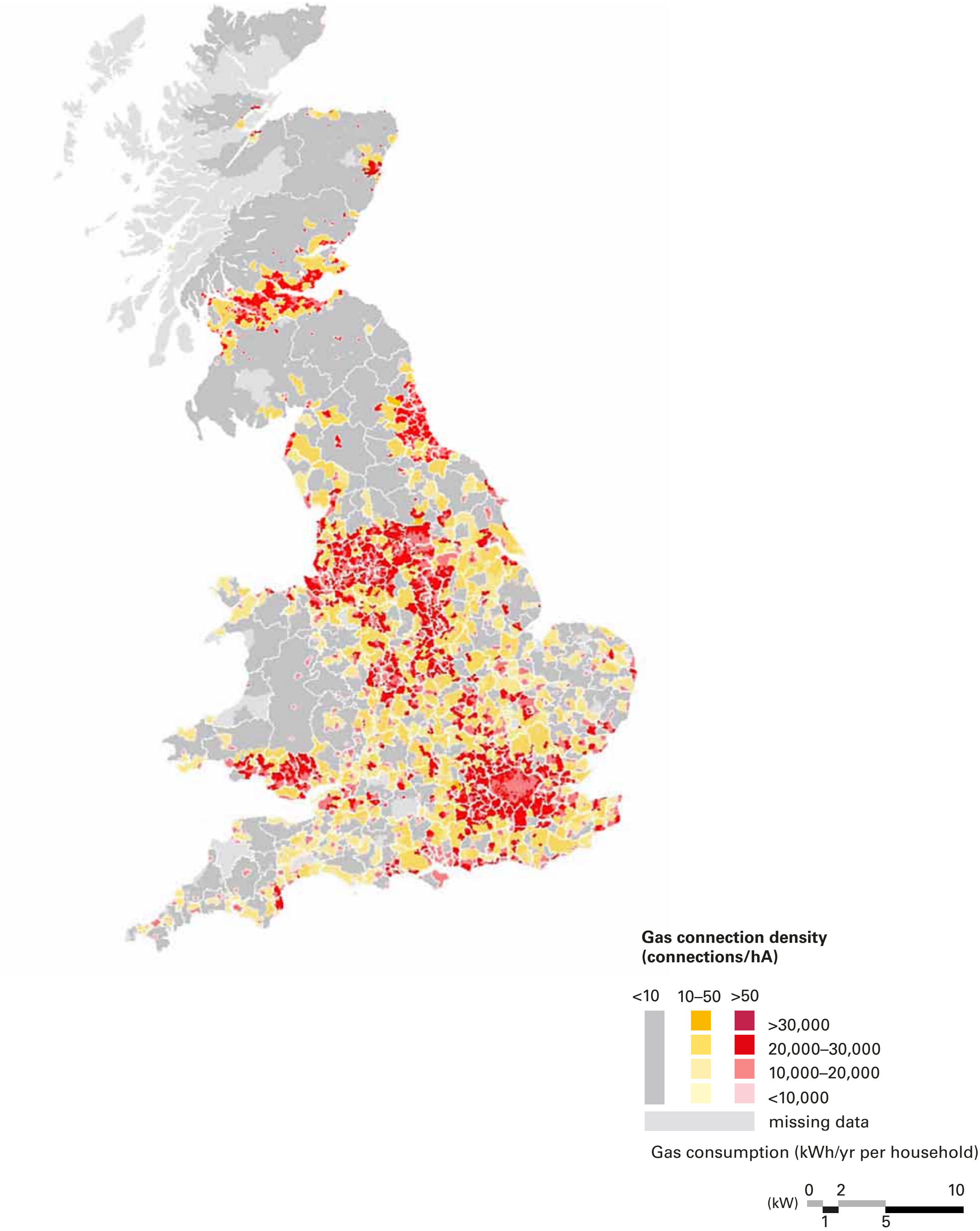
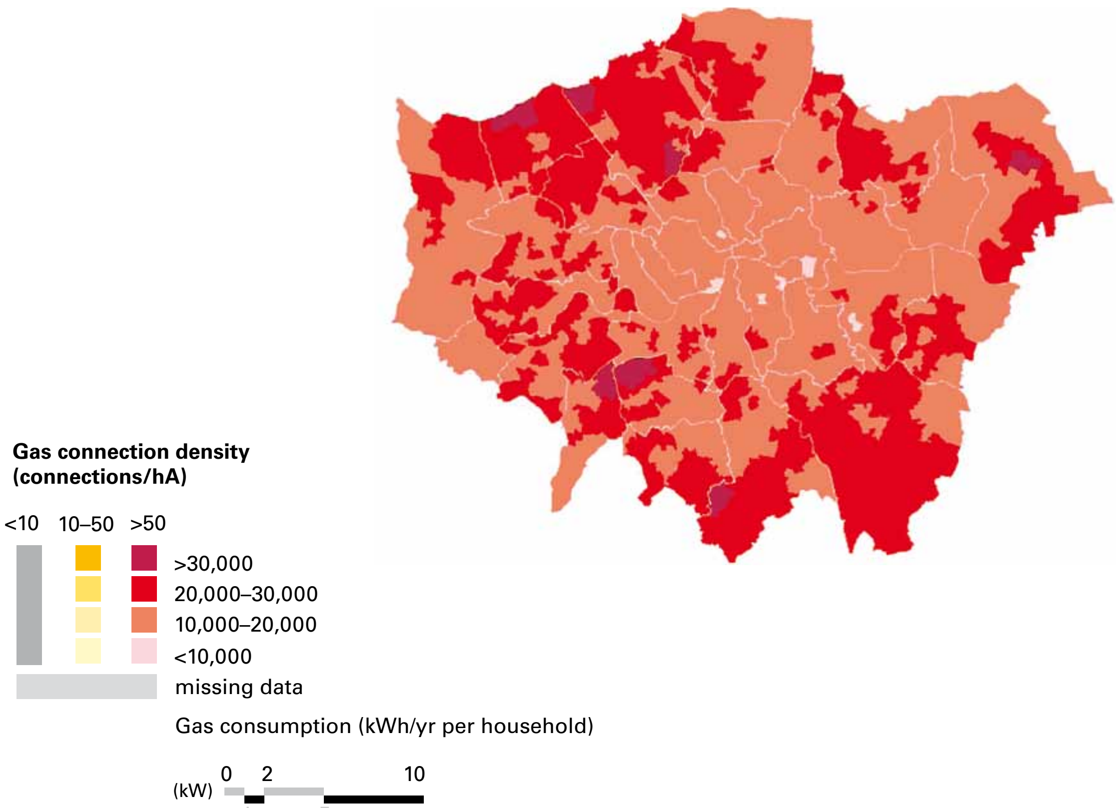


*Figure 6.3* Gas demand map for Greater London




This approach may be useful for micro-CHP developers to identify which parts of the UK may prove the most attractive markets for their products.

## Summary

- There are an estimated 8 million houses in the UK that may be suitable for micro-CHP systems similar to those in the field trial (i.e. with heat demands >14,000kWh/year).
- Around 170,000 boilers are sold annually in this market.
- Initial markets for micro-CHP systems may be concentrated in the suburban areas of the major cities, due to their high proportion of larger gas-connected houses.

## Small commercial applications

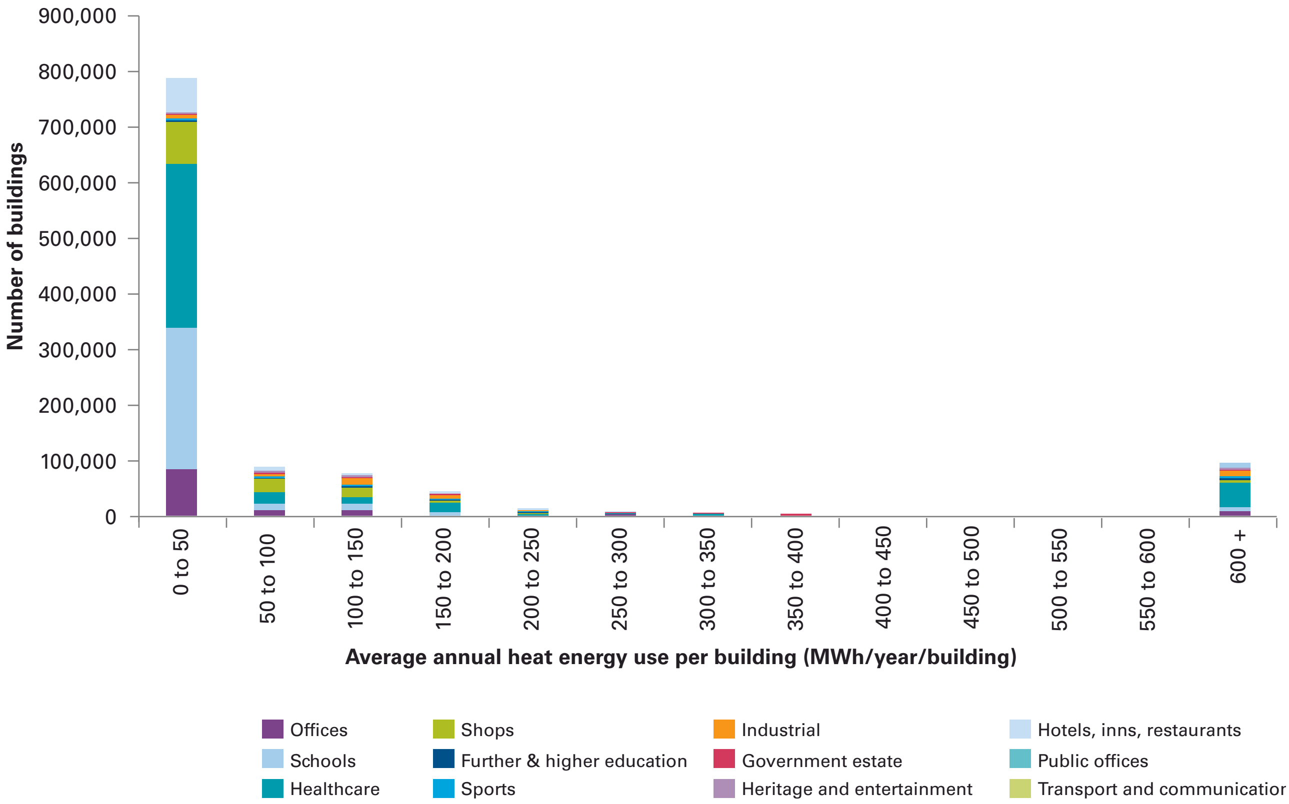
There is also a significant potential market for micro-CHP in non-domestic buildings.

There are an estimated 1.8 million non-domestic buildings in the UK, together accounting for around 18% of the UK's carbon emissions. Using data from the Carbon Trust's model of the UK's non-domestic building stock combined with standard benchmarks for the typical heat demand of different building types, estimates have been made to illustrate the potential market for small commercial micro-CHP.

*Figure 6.4* shows the estimated distribution of non-domestic buildings in the UK[22] by average annual heating demand per building. It shows that there are a large number of non-domestic buildings with heat demands of less than 50MWh/year, many of which may be appropriate for domestic scale micro-CHP units such as those featured in the field trial. Small high street shops and offices would typically be in this category.

[22] Building the future, today, Carbon Trust, CTC 765.

*Figure 6.4* *Distribution of UK non-domestic buildings by average annual heat demand*



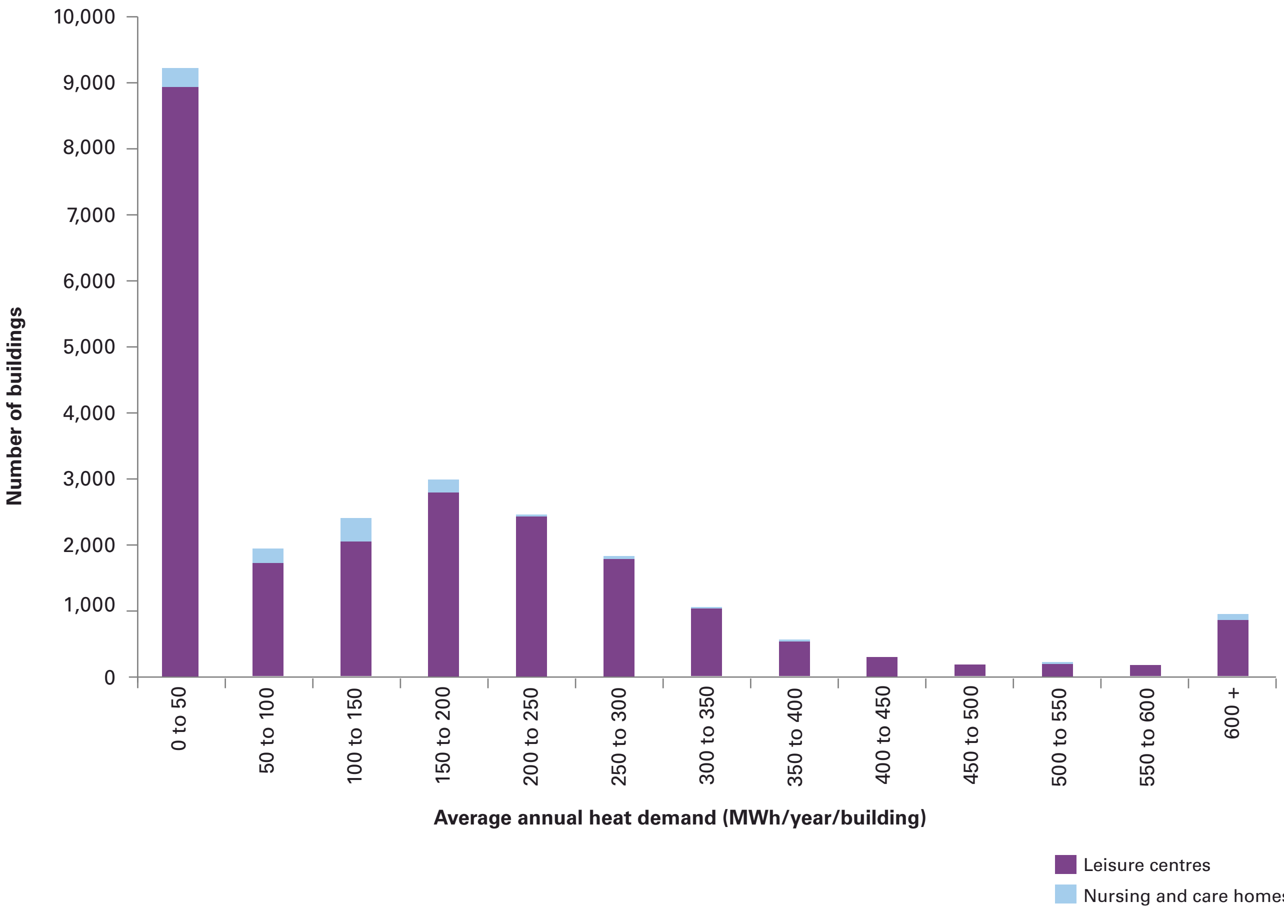

Around 20,000 commercial boilers are sold annually[23]. The most attractive sectors for IC-engine micro-CHP are likely to be those in which the heat demand per building is typically high and consistent, such as nursing and care homes and leisure centres. Many of the small commercial sites in the field trial were in these sectors.

*Figure 6.5* shows the estimated distribution of buildings in these sectors by heat demand per building. It shows that, due to the nature of these sectors, a disproportionately high number of nursing and care homes and leisure centres have heat demands greater than 50MWh/year. In addition, the proportion of buildings in these sectors connected to the gas grid is greater than 90%[24]. These sectors are therefore likely to be relatively attractive markets for IC-engine micro-CHP systems.

[23] Building Services and Environmental Engineer, July 2006.

[24] DUKES, Table 5.6.

***Figure 6.5*** *Distribution of UK leisure centres and nursing and care homes by annual heat demand per building*




Analysis in section 4.2 showed that small commercial micro-CHP systems installed as the lead boiler in a plant room could typically achieve a 16% overall carbon saving versus condensing boilers alone. Applying this figure across these two sectors, the potential carbon saving is estimated to be greater than 100,000t$CO_2$/year in around 20,000-25,000 buildings.

These sectors are also likely to be particularly attractive as they include a high proportion of buildings that are owned and occupied by local authorities. In other sectors such as offices and retail, landlord/tenant relationships are more common, and may act as a barrier to the installation of new low carbon heating systems such as micro-CHP

CTC788

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