Citation for published version:
Rogers, J 2013, 'A reconsideration of the use of domestic CHP in the UK domestic market', Paper presented at 3rd International Conference in Microgeneration and Related Technologies in Buildings: Microgen 3, Naples, Italy, 15/04/13 - 17/04/13.

Publication date:
2013

Document Version
Peer reviewed version

Link to publication

University of Bath

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 29. Oct. 2020

A RECONSIDERATION OF THE USE OF DOMESTIC CHP IN THE UK DOMESTIC MARKET

J.G. Rogers
University of Bath, Address, Bath, BA2 7AY, UK
*corresponding author: J.G.Rogers@bath.ac.uk
phone +44 (0) 1225 384550

ABSTRACT

UK climate change policy relies on a combination of nuclear power, renewable generation (mostly wind power) and carbon capture and storage to decarbonize the electricity grid. There are technical, economic or public acceptability issues with all elements of this strategy. Advancements in gas extraction technology mean that natural gas should be available for most of this century; consequently it is worth re-examining the use of gas fired micro combined heat and power units (CHP) as a way of meeting medium term emission reduction goals.

The Carbon Trust carried out field trials of micro CHP units in domestic and small scale commercial applications in England. Units based on Stirling Engines were used in domestic applications and found to produce only modest emission savings when compared to condensing boilers and grid electricity. Internal combustion (IC) engines were used in the commercial premises and these produced nearly twice the emission savings of the Stirling engines. The IC units were used with auxiliary boilers for peak and low load duties following established commercial CHP practice.

Currently small Stirling engine micro CHP plants receive feed in tariff payments in the UK but there is no support for small (IC) engine CHP schemes.

Unfortunately the field trials did not investigate heating groups of a few houses in the same way as a commercial property. This study models this option and expands it to integrate solar water heating into the system to reduce the need to run the system purely for hot water in the summer. It was found that by using thermal stores it is possible to satisfy traditional heating patterns while only running the CHP plant at times of peak electricity demand. As such they could form a key component in the national electricity mix as well as supplying low carbon heat.

Keywords: micro CHP, solar water heating, thermal modeling, energy requirement UK homes

INTRODUCTION

Sumary of carbon trust field trial finding

The field trials were conducted over 2006-2007 they included 72 Stirling engine micro CHP units installed in a range of houses selected to reflect the UK housing stock, 15 existing IC engine based units installed in applications like care homes and community heating schemes, and 36 houses with condensing boilers to provide bench mark data [1,2]. The installations were monitored on a five minute interval for 12 months. All installation had hot water storage tanks. The Stirling engines were installed as direct replacements for the central heating boilers. The commercial units had thermal stores and auxiliary boilers.

The following parameters were used to evaluate the systems: gas used, heat generated, gross electrical efficiency, gross heating efficiency and carbon benefit ratio. The carbon benefit ratio is defines as:

$$CBR = \frac{(heatout\ .CEF_{gas} + E_{gen}.CEF_{ele})}{(Gasin.CEF_{gas} + E_{used}.CEF_{ele})} \quad (1)$$

Equation 1 implies that gas is used to provide heat; this is the case in the vast majority of UK houses. The average CBR for the different systems are shown in Table 1.

Table 1 Carbon benefit ratios for systems tested in field trial

System	Average	top 10%
Boiler	82%	88%
Stirling Engine CHP	88%	96%
IC CHP	117%	130%

There was quite a wide variation in CBR between similar sites. An indication of the performance that can be achieved by following best practice can be inferred from the performance of the top 10% of sites for each type of heating system. The CBR for the domestic systems (boiler and Stirling) were found to drop down to 70% during the summer when the units were only required for water heating. The commercial systems had a lower seasonal dip. The CBR for the Stirling engine systems increased with thermal load and length of run. It was concluded that:

- IC engine CHP would produce carbon savings in commercial application.

- Stirling engine systems would produce carbon savings but only in households with higher heating loads.

Alternative application philosophy

The Carbon Trust trials adopted a philosophy that domestic micro CHP units should be a plug in replacement for domestic gas boilers. Unfortunately this is unlikely to result in them performing well. The main reason for this is the low thermal storage capacity in traditional UK heating system. The system design manual for the Stirling engine used in the majority of installations clearly states that thermal stores should be used if the average thermal load is less than 7kW [3], the Carbon Trust trial report gives the peak heating load of a typical UK house as 6kW [2] so a thermal store should have been fitted. The advantages of using thermal buffer stores with micro CHP systems is well documented [4,5]. Senertec recommend the use of a 750l thermal store with their Dachs unit [6]. Consequently the performance of the micro CHP systems may have been improved had thermal stores been installed.

The average size of boiler fitted into houses in the UK is 10-30 kWh [2], this reflects the requirement to replenish the hot water in a small hot water tank for a continuous supply of hot baths. If a thermal store of 300l is installed this requirement can be ignored as three baths can be taken from it without the outlet temperature falling below acceptable levels [7]. Consequently a smaller heating unit can be installed. The economic benefits of using an auxiliary heater to support a CHP unit are well established for industrial systems and have been considered for micro CHP [8]. If this is done, the thermal rating of the CHP unit would be in the order of 3 - 6 kW. It is noticeable that the Whispergen mk5 unit has a nominal thermal output of 7kW which can be boosted to 12kW with an auxiliary burner, as such it can supply two houses rather than a single house. However if a single micro CHP unit is going to supply multiple houses it is unlikely to be mounted in the occupied space of one of them. Consequently the lower noise levels of a Stirling engine become less of an advantage over an IC engine which has a considerably higher CBR than commercially available Stirling engines.

The running of main heating systems for short periods in the summer to provide hot water is bound to be inefficient due to the relatively high level of losses during the start up and shut down periods. If thermal stores are used it should be possible to use solar water heaters to provide hot water during the period when space heating is not required.

Consequently it was decided to model the performance of a range of small micro CHP units supplying a single house. The CHP units would have identical characteristics to commercial units so that in a real installation they could be realised by sharing a single CHP unit between a few houses (it is intended to develop a multi house model in the future). The system would be supported by an auxiliary boiler to maintain a minimum store temperature. The impact of using different sizes of thermal store and optional solar water heaters was investigated.

The CBR formula used by the Carbon Trust is likely to show an emission benefit simply because gas is being used as a primary fuel rather than the grid mix of coal, gas, nuclear and renewables. To get an assessment criteria which is independent of the grid mix it was decided to compare primary fuel usage between a benchmark house with a gas fired condensing boiler supplied with grid electricity from a gas fired combined cycle gas turbine (CCGT) power station with the gas used by a similar house with gas fired micro CHP, auxiliary boiler and grid electricity from a gas fired CCGT power station. As gas is the primary fuel in both cases it will give a true comparison between the technologies used.

Potential for solar water heating in the UK

Britain is often thought as a cool damp country with a wide variation in sun light across the country. However estimates of hourly irradiation that would have been received in a typical year at 12 cities across the UK have been taken from Exeter Universities PROMETHEUS web site [9]. The average daily irradiation for the summer period (arbitrarily defined as day 100 to day 250 of the year) was calculated as 4.6 kWh m^{-2} with a standard deviation of 1.5 kWh m^{-2}. This only varies by 17% across the country. Consequently solar water heating should be usable in areas where most of the people live.

DESCRIPTION OF MODEL

The core of the system is the thermal store. It receives heat from the CHP engine, auxiliary boiler, and solar water heater. It delivers heat to the radiator system and domestic hot water system (DHW). The CHP plant and auxiliary boiler are controlled by the temperature of the thermal store using separate thermostats with variable deadbands. The temperature of the store was calculated at the end of each 7.5 minute time period by

$$T_{n+1} = T_n + \frac{(\sum Heat\ in_n - \sum Heat\ out_n)}{(mass.Specific\ heat)} \quad (2)$$

All temperatures are assumed to be constant throughout the period. In order to keep the number of combinations manageable it was decided to consider three thermal store sizes: 300l, 500l, and 1000l.

Heat in

CHP

It was decided to look at combinations that are realisable with commercially available CHP engines. A heat supply of 12, 6 or 4 kW of heat can be achieved from different CHP engines by sharing them between 1 to 3 houses. It was decided to base the CHP engine model on the Senertech Dachs engine as its thermal characteristics have been studied previously and it was included in the Carbon Trust trials [6,17,18,2]. This engine has a lhv electrical efficiency of 26% and a lhv heat efficiency of 63% [6]. The heat produced in the first 7.5 minutes of each run was reduced by 90% to allow for the warm up period of the engine.

The CHP engine is prevented from running over some time periods. This prevents the CHP plant creating a noise nuisance by running early in the morning or late at night. The CHP plant should be used in preference to the auxiliary boiler so its cut in temperature is 5°C higher than the auxiliary boiler's. It is desirable for the CHP engine to be run for long periods so a high cut out temperature is desirable. The CHP engine will overheat if the coolants return temperature is too high. For the Dachs unit the recommended maximum return temperature is 75°C [6]. As there needs to be a temperature difference between the thermal store temperature and the CHP coolant circulating through the heating coil it was decided to stop the CHP unit when the thermal store temperature reached 65°C.

Auxiliary boiler

The auxiliary boiler is also prevented from running outside given time periods. It cuts in if the thermal store temperature drops below the design delivery temperature of the domestic hot water system (DHW) (assumed to be 50°C). Condensing boilers only condense if the return water temperature is below the water dew point of their exhaust and ideally less than 50°C consequently it is desirable to stop the auxiliary boiler at as low a temperature as is practical. In this case a cut out temperature of 60°C has been used. The auxiliary boiler was sized so that the total heating power of the boiler and the CHP engine would be 12 kW in all cases. The auxiliary boiler is assumed to have an efficiency of 83% which was the average achieved by condensing boilers in a field trial [19].

Solar water heater

Estimates of hourly beam and diffuse irradiation that would have been received at Heathrow for a year in the period 1961 to 1990 have been taken from Exeter Universities PROMETHEUS web site [9]. These have been used to calculate the hourly solar irradiation on an inclined solar collector. To maximise the use of solar energy it was decided to collect extra solar energy on sunny day and store it for use on cloudy ones. This meant that the solar collector would have to operate efficiently with a high collection temperature. A collector that uses vacuum tube heat pipes would be suitable for this duty and it was decided to model the performance of the Sunnpro series of solar collectors as they appeared to be typical of this type of collector [10]. The collector was assumed to be optimally mounted and the area adjusted such that the store temperature did not exceed 90°C. The amount of energy that can be stored on a sunny day is naturally a function of the store size; a larger collector area is needed to collect more energy consequently the size of solar collector that can be installed increases with store size. The following collector areas were used for the different store sizes:

- 4 m^2 collector with 300 l store
- 5 m^2 collector with 500 l store
- 7 m^2 collector with 1000 l store

Solar Gain

The solar energy received per square meter of south facing window for each day has been calculated using the hourly solar data for Heathrow and the following factors from the SAP procedure [11]: frame factor of 0.7, transmittance 0.76, solar access factor 0.9. It was assumed that the house would have the equivalent of one south facing wall with a window area of 5.44m^2 (glazing fraction of 17% from [11]) and that the solar gains through the other walls would be negligible.

Metabolic and cooking

Metabolic gain is the heat given off by the occupants of the dwelling. The SAP procedure [11] assumes that the heat dissipation to the surroundings is assumed to be 100 Watt per person. 80% of English households have less than 4 occupants [12] so it was decided to assume an occupancy level of 3 for calculating the metabolic gain and DHW demand. No attempt was made to model the occupancy pattern of the house on the assumption that the occupants would not mind the property being slightly colder if they were not in it. The SAP procedure [11] uses equation 3 for average cooking gain

$$gain = 35 + 7\,N\ kWh/day \quad (3)$$

It would be more realistic to consider that cooking only take place in the hours 12:00 to 13:00 and 18:00 to 19:00 this would then give cooking loads for these periods of, 0.672 kWh for occupancy levels of 3.

Lighting and appliance gain

It was assumed that eventually all electrical power used in the home would end up as heat. The standard 30 minute demand profiles used by the electricity balancing market administrators [14] was used to estimate the hourly electricity consumption which would give a typical annual consumption of 3545 kWh.

It was found in a trial of solar water heaters that they had an electricity consumption equivalent to 7% of the heat they collected [20]. Boilers electrical loads are around 2% of their thermal output. Consequently the electrical load has been increased when solar water heaters are used.

Thermal Store losses

As the thermal store is assumed to be in the heated area of the house the heat loss from it is a heat gain for the house. The Hot Water Association standard for heat stores [7] gives the following equation for calculating the maximum permitted 24 hour heat loss from a heat store installation in a new building:

$$QHL\text{-}MAX = 1.28 \times [0.2 + 0.051\,(VT)^{2/3})] \quad (4)$$

Where *QHL-MAX* is the maximum permitted daily heat loss from a thermal store in kWh and *VT* is the total storage capacity of a thermal store in litres. It is tested with an initial store temperature of 75°C, and an ambient air temperature of 20°C. This does not reflect the conditions the store is use in but it has been used to calculate an average heat loss coefficient on the basis that the rate of heat loss will be proportional to the difference in temperature between the store and the ambient air so:

$$\Delta Q/\Delta t = K\,(Tw - Ta) \quad (5)$$

The value of K for a range of store sizes is shown in Table 2.

Table 2 Heat loss constants for thermal stores

Volume	Q_{HL-MAX}	ΔT_{24}	K
l	kWh	°C	kJ/h°C
300	3.18	9.13	9.46
500	4.37	7.52	12.79
1000	6.78	5.84	19.54

ΔT_{24} Is the temperature drop of the store after 24 hours.

Heat out

Radiator system

Radiator based central heating systems are well established and can be assumed to work so there is no need to model the workings of the heat distribution system. When running, the radiator system supplies the net loss from the building and stores heat within the building fabric. When the radiators are not running the net heat loss is supplied by the heat stored in the building fabric. The output of the radiator system is a function of the thermal store temperature.

Domestic hot water

The Energy Saving Trust [14] carried out a survey of DHW usage in the UK which gave averages for the volume used, delivery temperature, and incoming water mains temperature. This has been used to derive the following equation for the average DHW energy requirement:

$$Q_{dhw} = 4.56 + 6.53N\ MJd^{-1} \quad (6)$$

The report includes a water usage profile taken from the hourly average consumption of all the house included in the survey. This included some usage throughout the night. It is unlikely that people use hot water in their sleep so this figure is the results of a higher usage by a few people with nocturnal habits rather than a low general usage. To overcome this anomaly it was decided to allocate the total energy used between 21:00 and 7:00 equally between the 6, 21, 22, and 23 hourly time periods. This profile is shown in Figure 1. It has been reported that DHW consumption reduces in the summer [11,13] and that the mains water temperature is higher in the summer these factors have been combined to give a monthly adjustment factor to be applied to the consumption calculated from equation (6). This is shown in Figure 2.

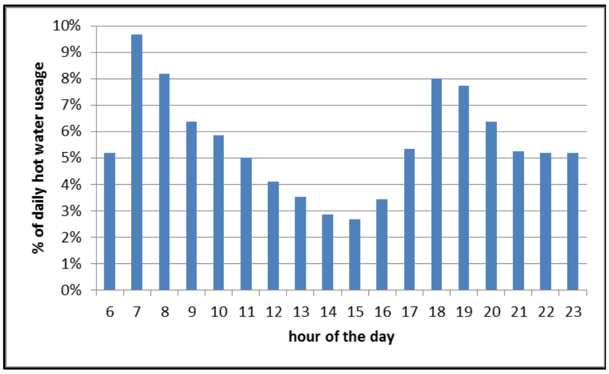

Figure 1 DHW daily usage profile

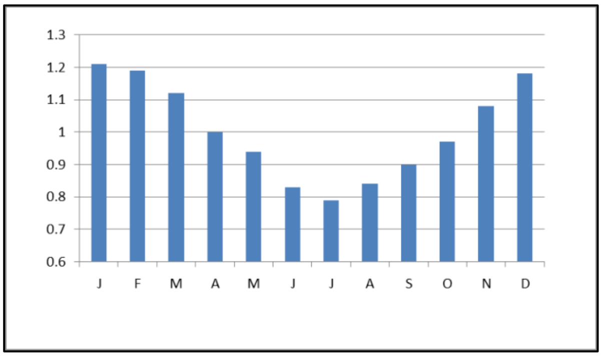

Figure 2 monthly adjustment factors for DHW usage.

Heat loss

The most common type of house in Britain is a three bedroom semi-detached or terraced house with a floor area of 82m^2 [12,15]. There is a wide range of construction techniques used so the thermal conductivity and thermal mass will vary between houses. Three common construction styles are considered:

Type 1 - typical early 20th century construction of facing brick, air cavity, and inner brick skin with a plaster facing. There have been a number of government schemes to improve the insulation standard of houses and it has been assumed that type 1 properties would have had the loft insulated to a depth of 100mm, cavity wall insulation injected and double glassing fitted over the last 30 years.

Type 2 houses - typical mid 20thcentury these are similar to type 1 houses but the inner skin of the cavity wall is made of cinderblock rather than brick. Again it was assumed that the insulation improvement measures implemented on the type 1 houses have also been carried out on the type 2 house.

Type 3 houses - built to current building regulation.

It is assumed that a typical house is a cube with a pitched roof that is joined to a similar house by a common wall. Glazing fraction and material U values were taken from the government's Standard Assessment Procedure manual for the energy ratings of dwellings [11]. This gave the following heat loss from the different building types:

- Type 1, 180 W/K
- Type 2, 167 W/K
- Type 3, 89 W/K

An allowance for ventilation loss has also been included. Test on a range of property types in Scotland found ventilation rates in mid-winter ranging from 2.15 to 0.05 air changes per hour (ACH^{-1}). Some of this variation can be accounted for by building type, and age however there was also a wide range of values within each type of building indicating differences caused by location, or user preference [16]. It was decided to use the following ventilation losses:

- Type 1, 1.6 ACH^{-1} 118 W/K
- Type 2, 1.0 ACH^{-1} 73 W/K
- Type 3, 0.4 ACH^{-1} 29 W/K

This gives the total losses for the three building types of

- Type 1, 298 W/K 3.66 W/m^{2}K
- Type 2, 240 W/K 2.93 W/m^{2}K
- Type 3, 119 W/K 1.45 W/m^{2}K

This compares with the average value of 247 W/K for the UK housing stock from the domestic energy fact file [17].

Thermal storage

Heat is stored in the fabric of the buildings. The amount of heat stored depends on the temperature of the building element and its thermal mass.

Table 3 Heat stored in each element of the wall

	Type 1	Type 2	Type 3
outer skin	8.1	6.5	4.6
insulation	0.2	0.4	1.1
inner skin	180.4	72.3	84.8

Table 3 gives the heat storage per 1°C difference in temperature across the wall in kJ m^{-2} K^{-1}. It shows that nearly all of the heat storage occurs inside the insulation envelope of the building. Consequently it was decided to assume that the only significant heat storage is in the inner skin of the outside walls and the internal walls. The thermal masses for the building types being considered are:

Type 1, 18,516 kJ K^{-1},
Type 2, 8,333 kJ K$^{-1,}$
Type 3, 9,17 kJ K^{-1} .

Acceptability criteria

Plant combinations or operating constraints that resulted in the thermal store temperature dropping below 40°C (commonly assumed minimum acceptable level for DHW) or to a level where the radiator systems capacity was lower than the power that it was required to deliver were considered to be unacceptable to the occupants.

Operation periods

Radiator system
It was decided to follow common UK practice and run the radiator system between 06:00 - 10:00 and 16:00 - 22:00.

Auxiliary boiler
The purpose of the auxiliary boiler is to provide heat when the CHP plant can't cope. Given that the size of thermal stores being considered will supply over a day's DHW the assistance of the auxiliary boiler should only be required when the radiator system is able to run.

CHP
There could be some advantage to the grid if they had control over when a large number of micro CHP plants started so it was decided to look at the impact of delaying the start of the CHP plant by one and two hours from the start of the radiator system.

Parameters calculated

- CHP starts in year
- CHP running days in year
- Average number of starts on running days
- Maximum starts in any day
- Average running hours per day on running days
- Fraction of heat load provided by the CHP
- CHP capacity factor
- CHP annual heating efficiency
- Primary fuel saving when compared to all gas system for grid electricity and local heating
- Net annual electricity consumption
- CHP running patterns

RESULTS AND DISCUSSION

Unless stated otherwise all results are for type 2 houses as these have loss characteristics that are close to the national average.

Primary energy savings

Figure 3 shows the primary energy saving for the different plant combinations. In all cases the 6kW CHP engine gave higher savings than the 12kW ones. This is due to the higher efficiency acheived by the 6kW installation shown in Figure 11. The 4kW installations have marginally higher efficiencies than the 6kW ones but the advantage of this is outweighed by the increased use of the auxiliary boiler in the 4kW installations and their lower electrical generation as shown in Figure 4.

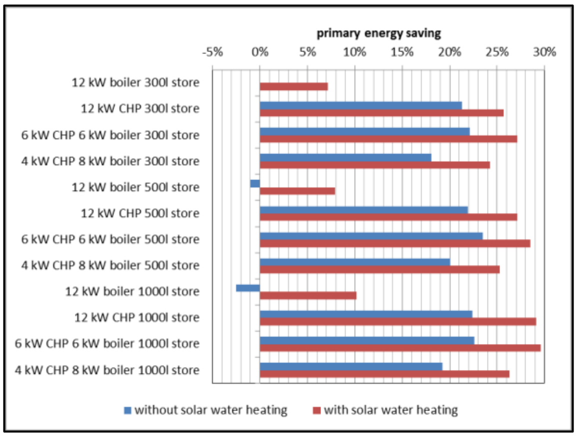

Figure 3 net primary energy savings

The impact of adding solar water heaters to the 12kW boiler installations is relativly higher than adding the same solar pannels to the CHP systems. This is due to the reduction in electricity generation resulting from lower CHP running hours when solar water heating is used.

The increase in primary energy use with store size in the boiler only cases reflects the increased thermal losses from the larger stores.

It is worth noting that the benchmark case of CCGT generated grid electricity and gas condensing boilers gives a 32% reduction on the emissions that would have occured with a 1990 grid mix and non condensing boilers so a 25% primary fuel saving against this papers benchmark is a 49% saving against the Kyoto protocol baseline.

Electricty production

Figure 4 shows the net electricity import for the different plant combination. The electricity import is expressed as the ratio of the annual net electricity import to the annual load for the house using a 12 kW boiler with 300l store and no solar water heating. It should be remembered that domestic electricity consumption is stochastic and a low net electricity import results from the export to the grid being of the same order as the electricity imported from the grid.

As the total heat demand should increase with store size (due to increased losses) it may be expected that generation will increase with store size. However the reverse is true for the 12kW installations; the reason for this is the improvement in annual heating efficiency with increasing store size for these installations.

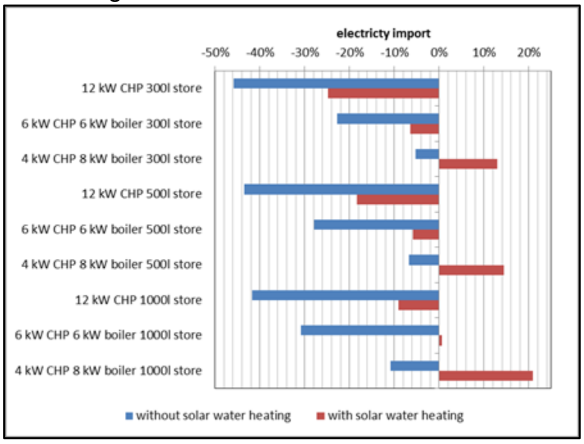

Figure 4 net annual electricty imports

Run patterns

Figures 5 to 8 show the proportion of each hour that the CHP plant runs on various days throughout the year. The impact of reducing the CHP plant size on running patterns can be seen in Figures 5 & 6.

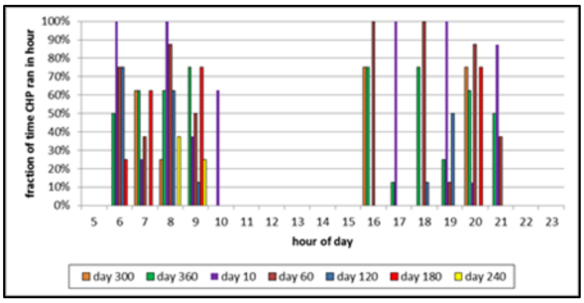

Figure 5 run pattern for 12 kW CHP and 300l store without solar

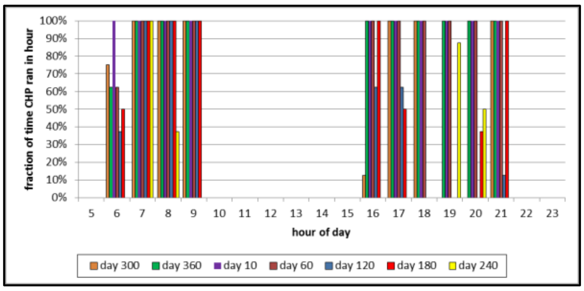

Figure 6 run pattern for 4 kW CHP and 300l store without solar

Figure 5 shows short runs with some incidences of multiple starts in the morning period. The runs in Figure 6 last for longer periods and could be relied upon to generate over the morning and evening peak electrical demand periods in the winter.

Figures 5 and 7 show the impact of increasing the store size on running patterns. Increasing the store size also reduces multiple starts but it does not produce the reliable peak hour generation pattern seen in Figure 6.

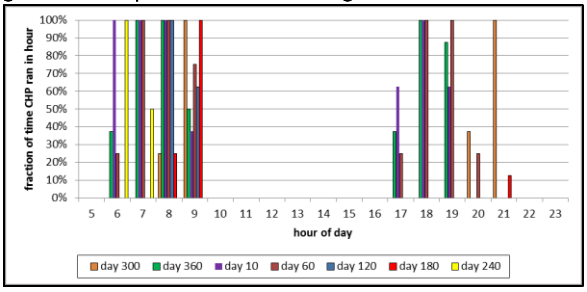

Figure 7 run pattern for 12kW CHP and 1000l store without solar

There appears to be a large discrepancy in the running hours on day 240 between Figure 5 and 7. In the summer the CHP plant is only used for DHW. The engine will run for the length of time required to reheat the thermal store, consequently it will run for 3 times longer with the 1000l store than it would for the 300l one. This is compensated for by the fact that in the summer the engine with a 1000l store does not need to start every day (Figure 9).

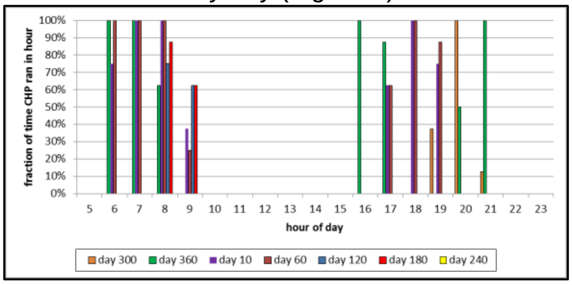

Figure 8 run pattern for 12kW CHP with solar water heater and 1000l store

Comparison between Figures 5 and 8 show the impact of adding solar water heaters. As may be expected this reduces the running hours in the summer.

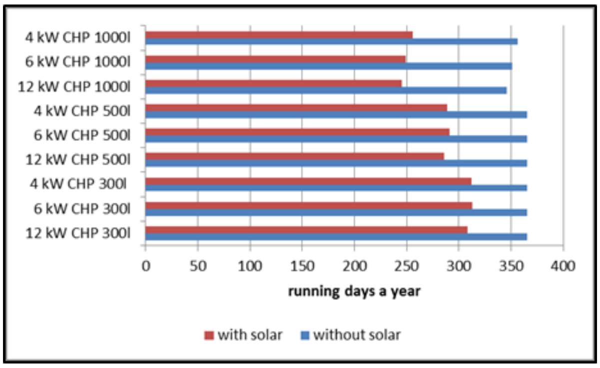

Figure 9 CHP running days

Heating efficiency

The annual heating efficiency achieved by the CHP engine will be a function of the number of starts that the engine makes and the length of each run. Figure 10 shows the annual thermal efficiency and the average number of starts per hour run for all the combinations considered.

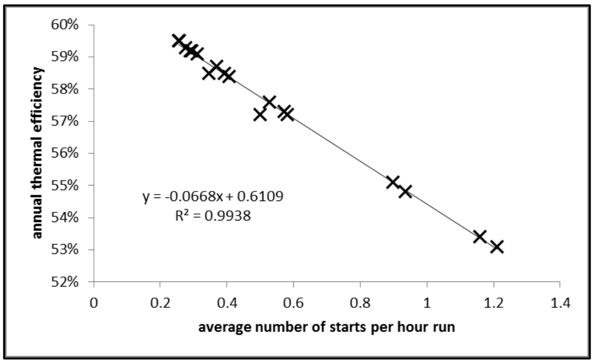

Figure 10 heating efficiency

The starts per running-hour ratio will be a function of the CHP size and store size as shown in Figure 11.

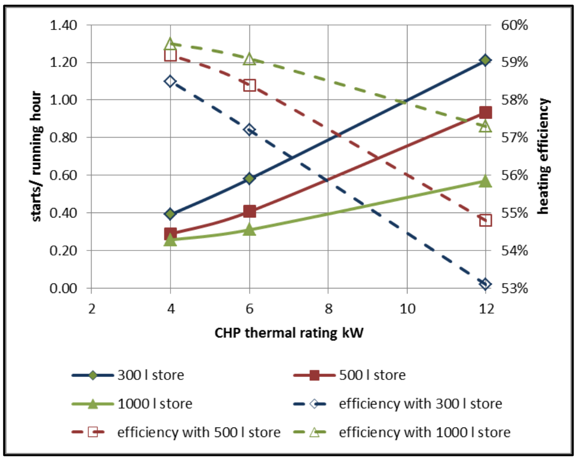

Figure 11 influences on the start running hour ratio and heating efficiencies

Figure 11 show data for units without solar water heating.

Load factors

Reducing the CHP unit size does improve the starts per running-hour ratio but the auxiliary boiler operates more frequently for installations with smaller CHP units as identified in Figure 12. The CHP units can supply more than 100% of the primary energy as the exported electricity is considered to be a negative flow. As solar water heating is mainly available in summer it is not surprising that its impact is to reduce the CHP running rather than that of the boiler.

Impact of delaying CHP start

The effect of delaying the start of the CHP plant is to increase the load on the auxiliary boiler. This reduces the running hours of the CHP and the associated electricity generation.

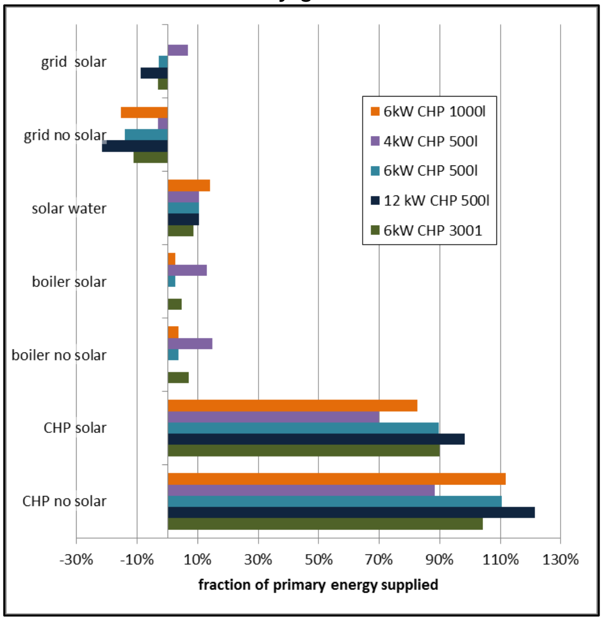

Figure 12 load factors

Table 4 shows the impact on the CHP primary fuel savings caused by delaying the start of the CHP unit (the radiators and auxiliary boiler running times are not changed).

Table 4 primary fuel savings for different start delays

		delay		
CHP	Store	no	1hr	2hr
6	300	22.1%	16.9%	12.1%
4	300	18.1%	15.5%	10.3%
6	500	23.5%	18.9%	14.0%
4	500	20.1%	16.8%	11.9%
12	1000	22.4%	22.6%	22.7%
6	1000	22.6%	20.8%	17.6%
4	1000	22.1%	16.9%	12.1%

Table 4 covers installation without solar water heaters. In these cases the load is split between the CHP plant and boiler so any reduction in CHP load is taken up by the boiler. As the 12kW system has no boiler all the heat for the period of the delay must come from the thermal store, it was found that this was only possible with 1000l stores. Delaying the CHP start means that the store will be feeding heat into the radiator system for the period before the CHP is allowed to run. This will lower the store temperature which will increase the chances of the CHP unit running when it is enabled. The impact of this can be seen by comparing Figures 7 and 13.

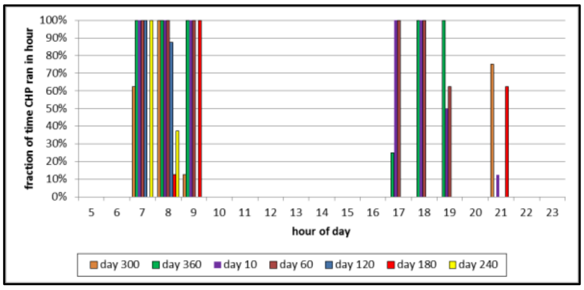

Figure 13 run patter for a 12 kW CHP unit with 1000l store and a one hour start delay

Impact of different building types

Many of the running parameters for type 1 and 3 houses are similar to those for a type 2 house some noticeable exceptions are shown in Table 5. Table 5 is for buildings fitted with 1000l thermal stores and solar water heaters. There is a large difference in heating requirements between the building types. 40% of the heat requirement for the type 3 house is actually provided by the solar water heater consequently the size of the CHP unit has been reduced for this building type so that it had similar operating regime to those on the other building types.

Table 5 comparison of different building types

building type	1	2	3
CHP size kW	6	6	3
heating kWh	14913	11440	6035
net primary fuel kWh	17743	14857	10987
electricity import %	-27.9%	1.0%	58.4%
capacity factor	20.8%	16.2%	13.4%
running days	272	249	197

The low heating requirement of the type 3 building leads to the electricity generated by the CHP being far less than that consumed on site. The resulting high electricity import fraction increases the net primary fuel used. The opposite is true for the type 1 house where the high electricity exports offset some of the gas consumption to give a reduced net primary fuel use.

CONCLUSION

It has been show that with suitably sized CHP engines and thermal stores it should be possible to achieve at least 20% primary fuel saving. This figure can be increased by 5-8% by adding solar water heaters to the installation. This corresponds to a 49% emission saving when compared to the Kyoto protocol base line date.

The annual thermal efficiency of a CHP unit reduces as the ratio of its number of starts to running hours increases. This can be optimised by reducing the CHP unit size or increasing the store size. However too small a CHP unit causes increased running of the auxiliary boiler which reduces the primary fuel saving. Too large a CHP unit for a given store size leads to short run times and lower thermal efficiency.

Traditional radiator systems can be supplied by thermal stores that are heated by small CHP units that are restricted to run over the morning and evening electricity peaks. As they run consistently during the winter period it would be possible to consider them as peak lopping generation plant.

Providing large thermal stores are used there appears to be some scope to bring forward or delay the running of CHP plants to help balance the grid. However delaying the start of CHP units reduces the primary energy saving that they achieve so this facility should be used sparingly.

Higher primary fuel savings can be achieved in buildings with higher heat loads. But it is worth remembering that the total heat load for the type 1 house is 15.3 MWh a^{-1} with 11.5 MWh a^{-1} and 6.1 MWh a^{-1} for the type 2 and 3 houses so the actual primary fuel used is much lower for the type 3 house. There would appear to be limited scope for CHP usage in highly insulated houses.

Given the real fuel savings that this established technology can make and the assistance that it could give the grid the case for giving it some sort of support should be reconsidered. But the systems must be correctly sized and used with thermal stores rather than traditional hot water tanks.

ACKNOWLEDGMENT

The author would like to thank Prof Geoff Hammond, Dr Marcelle McManus, Dr Adrian Winnett Mrs Hayley Howard and Mr Samuel Cooper for their advice and support during conducting this research. This research is carried out as part of the SUPERGEN:HiDEF program funded as part of The Energy Programme an RCUK cross-council initiative led by EPSRC and contributed to by ESRC, NERC, BBSRC and STFC

NOMENCLATURE

CEFgas = carbon emissions factor for gas (kgCO2/kWh)
CEFele = carbon emissions factor for electricity
E_{gen} = Electricity generated
E_{used}= Electricity used by CHP unit and heating system

Tn = Thermal store temperature during period n
Q_{dhw}= daily energy required for domestic hot water
N= number of occupants
K = the heat loss constant for the heat store
Ta = ambient air temperature around the store,
Tw = average temperature of the water in the store.

REFERENCES

[1] Carbon Trust, Micro-CHP Accelerator Interim report November, 2007, Carbon Trust report CTC726,2007

[2] Carbon Trust, Micro-CHP Accelerator
Final report – March 2011, Carbon Trust report CTC768, 2011

[3] Whispergen Tech ltd, Whispergen Mk 5 System design manual, Part No. WP-5037-025-00 UK, 2006

[4] Haeseldonckx D, Peeters L, Helsen L, D'haeseleer W, The impact of thermal storage on the operational behaviour of residential CHP facilities and the overall CO2 emissions, Renewable and Sustainable Energy Reviews 11(2007),1227–1243,

[5] Beyer D, Kelly, Nick N, Modelling the behaviour of domestic micro-cogeneration under different operating regimes and with variable thermal buffering. In: Micro-Cogen 2008,1st International Conference on Micro-Cogeneration Technologies and Applications, 29 April -01 May 2008, Ottawa, Canada.

[6] SenerTec, Instructions for Installation, assembly, commissioning and assembly of Dachs, Art No 07/4798.232.102

[7] The Hot Water Association, Performance Specification for Thermal Stores,2010 www.hotwater.org.uk

[8] Shaneb OA, Coates G, Taylor PC Sizing of residential CHP systems, Energy and Buildings, 43 (8), 2011,1991-2001.

[9] Exeter University. PROMETHEUS web site http://centres.exeter.ac.uk/cee/prometheus/. accessed October 2011.

[10] Kramer K., Test Report: KTB Nr. 2007-07-ac-en for Sunny Pro SP series, Fraunhofer-Institute for Solar Energy Systems ISE, Heidenhofstraße 2, D-79110 Freiburg, www.kollektortest.de;2007

[11] BRE, The Government's Standard Assessment Procedure for Energy Rating of Dwellings 2009 edition incorporating RdSAP 2009 Published on behalf of DECC by:BRE Garston, Watford WD25 9XX, 2011.

[12] Anon, Housing in England 2007–08, A report principally from the 2007– 08 Survey of English Housing September 2009. Department for Communities and Local Government, London, 2009.

[13] The Energy Saving Trust, Measurement of domestic hot water consumption in Dwellings, 2008 available from http://www.decc.gov.uk/publications

[14] UKERC Data Centre ,http://data.ukedc.rl.ac.uk/browse/edc/Electricity/LoadProfile/data/ProfileClass1.csv accessed March 2012.

[15] Utley JI and Shorrock DL, The BRE Domestic Energy Fact File 2008.

[16] Howieson S.G.,Domestic ventilation rates, indoor humidity and dust mite allergens - Are our homes causing the asthma pandemic?, Building Services Engineering Research and Technology, 24 (3), p 137-147, 2003.

[17]Beausoleil-Morrison I, Kelly N,. Specifications for Modelling Fuel Cell and Combustion-Based Residential Cogeneration Device within Whole-Building Simulation Programs. A Report of Subtask B of FC+COGEN-SIM The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems. Annex 42 of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme, 2007.

[18] Beausoleil-Morrison I, Kelly N, 2007b, Experimental Investigation of Residential Cogeneration Devices and Calibration of Annex 42 Models. A Report of Subtask B of FC+COGEN-SIM The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems. Annex 42 of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme, 2007

[19] Kershaw H, Lelyveld T, Burton S, Orr G, Charlick H, Dennish T, Crowthe M,.In-situ monitoring of efficiencies of condensing boilers –TPI control project extension. Report prepared for the Energy Saving Trust under contract GaC3700, 2010.

[20] Martin C., Watson M., Side by side testing of eight solar hot water heating systems. ETSUS/P3/C0275/REP/2, DTI pub URN 01/1296,2001