The role of micro CHP within a decarbonising energy system

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There is currently considerable debate as to the potential role for micro CHP and other low carbon technologies within an energy system that is becoming increasingly decarbonised and may ultimately become carbon neutral. It is argued by some that as the carbon content of the grid supplied electricity reduces it will eventually reach a point at which natural gas fired micro CHP no longer makes an effective contribution to reducing carbon emissions and, as the grid decarbonises further, micro CHP actually increases carbon emissions.

These observers tend to overlook the importance of transitional measures and thus underestimate the potential contribution of micro CHP to a long term, sustainable low carbon energy system.

Indeed, government analysis, focused on 2050 scenarios[1] does not even include micro CHP in its portfolio of technology options, let alone attempt to quantify the short term carbon mitigation potential of this technology.

There are two key issues which need to be understood before we can assess the role of micro CHP, or indeed any other technology, in a sustainable energy system.

The first is that each technology within the energy system has its own generation (or consumption) characteristics and, perhaps more importantly, these characteristics should not be viewed in isolation, but as part of an interactive relationship with one another; this applies equally to large scale central plant and to microgeneration technologies. Failure to understand this fundamental concept has led to the advocacy of many naïve policy scenarios which, whilst superficially attractive, simply cannot work – or at least cannot work at a feasible cost – given the realities of the technologies under consideration.

Secondly, whilst we may have a well considered vision for a robust long term energy system, in which we are able to meet all our energy needs from low or zero carbon resources, it is inevitable that we will have to accept certain compromises during the transition from our current system to that long term solution; furthermore in order to minimise the accumulated carbon burden and its consequent impact on climate, we should seek to minimise carbon emissions as soon as possible during that journey.

The UK CCC (Climate Change Committee) Renewable Energy Review[2] recently concluded that we could solve our energy challenges with a mix of 40% renewables, 40% nuclear and 15% CCS by 2030. Whether this is plausible, given that renewables are largely intermittent and not dispatchable and that neither CCS equipped thermal plants, nor nuclear are particularly well-suited to load following[3], whether it is achievable within anything like the proposed timescales or whether it is even desirable is a matter of debate. Indeed, many leading figures in both renewable and nuclear camps have observed that renewables and nuclear at this scale are mutually incompatible[4], on both resource and technical grounds.

How do we get to 2050?

Assuming that we wish to arrive at the all-electric future, and that the scenario outlined above is viable once in place, how do we intend to get there?

Leaving aside for now the security of supply issue and focusing on the climate change imperative, we need to consider not just the percentage reduction in annual emissions at some future point, but also the cumulative carbon burden. Put simply, climate change if caused, as is widely accepted, by carbon dioxide and other greenhouse gas emissions, is a result of the absolute concentrations of those gases in the atmosphere.

It is therefore essential that we implement pragmatic short term lower carbon solutions to mitigate cumulative carbon, rather than focusing solely on the end game, and thus missing cost effective opportunities to bank carbon savings during the transition to a low carbon future.

Unlike central plant solutions which take 10 years or more to construct and then need to operate for several decades in order to recover their capital investment, micro CHP systems can be installed in place of gas boilers at a rate of up to 1.5GWe annually and deliver low carbon electricity from the first day[5]. Furthermore, if at the end of the ten year boiler replacement cycle the grid has actually decarbonised to the extent projected, it is a simple matter to replace the micro CHP unit with some other technology, more suited to the emerging environment. In other words, central plant investment such as nuclear ties us into a fifty year or longer cycle which is unable to respond as flexibly to changing demands as micro CHP which is not only flexible, but is also an incremental and low risk “no-regrets” investment.

And, although we may need to review the merits of micro CHP in another decade or so, as will be shown below, the carbon mitigation benefits of this technology in today’s energy system are compelling. There is a clear environmental case for investment in micro CHP today.

Turning now to the security of supply issue, even without the aspirations for electrification of both heat and personal transport, the UK faces the serious risk of a supply shortfall within this decade. Due to various factors such as enforced closure of oil and coal and of life expiring nuclear plants, we expect to see a 45% capacity shortfall by 2016[6]. No-one, not even the most optimistic nuclear advocate is expecting adequate nuclear generating capacity to become available to meet that shortfall. Nor, given the inconsistent and uncertain policy framework, is it likely that a large scale solution of any kind will be constructed[7]. Indeed, there are some who believe that supply shortage might unintentionally help us meet our carbon emissions targets…albeit at the cost of a crippled economy[8].

We have been here before

It has often been stated that those who do not study history are doomed to repeat it; it seems that our government not only fails to grasp the integrated nature of energy systems, neither do they study history.

Just as earlier environmentally motivated legislation had unintended consequences for the UK electricity system half a century ago, so today we run the risk of imposing an unsupportable burden on our current electricity system to deliver decarbonised heat and transport systems.

Following the London smog of 1952 which led to thousands of deaths, legislation was passed to prohibit the combustion of the most polluting fuels[9] in urban areas. Not altogether surprisingly, having grown accustomed to relatively warm homes, many households switched to electric fires as a means of heating, just as they had done in the winter of 1947 when extreme cold weather and a shortage of coal left little alternative. By the early 1960s electric heating had become so widespread that when the harsh winter of 1962-3 arrived the entire electricity system collapsed. Our reaction to this situation was to build more robust distribution networks and more power stations, bigger power stations, remote from where the power was needed and dumping more than 60% of the primary energy into the atmosphere.

Other countries adopted a rather more sensible solution to this challenge, constructing communal heating systems making use of the primary fuel to generate electricity and simultaneously to provide heating to their communities, thus utilising more than 80% of the value of their fuel supplies. So whilst the UK squandered its valuable, but finite fossil fuel resources, dumping enough energy up the cooling towers of its central power plants to meet the entire UK heat demand, Denmark became self-sufficient in energy with an economy growing by 75% in real terms[10].

And now, 50 years on the CCC is proposing substantially increased use of electricity to decarbonise the UK energy system with scant consideration as to where this electricity will come from in the short term and a rather complacent view of the appetite and ability of generators to make the necessary investments in the longer term.

Heat Pumps or micro CHP?

There will be those who will challenge the electrification of the heat sector at all, given the inherent waste of heat in existing and proposed future electricity only thermal power stations[11]. However, assuming that is our long term goal, are heat pumps the most effective way to decarbonise the domestic heat sector anyway?

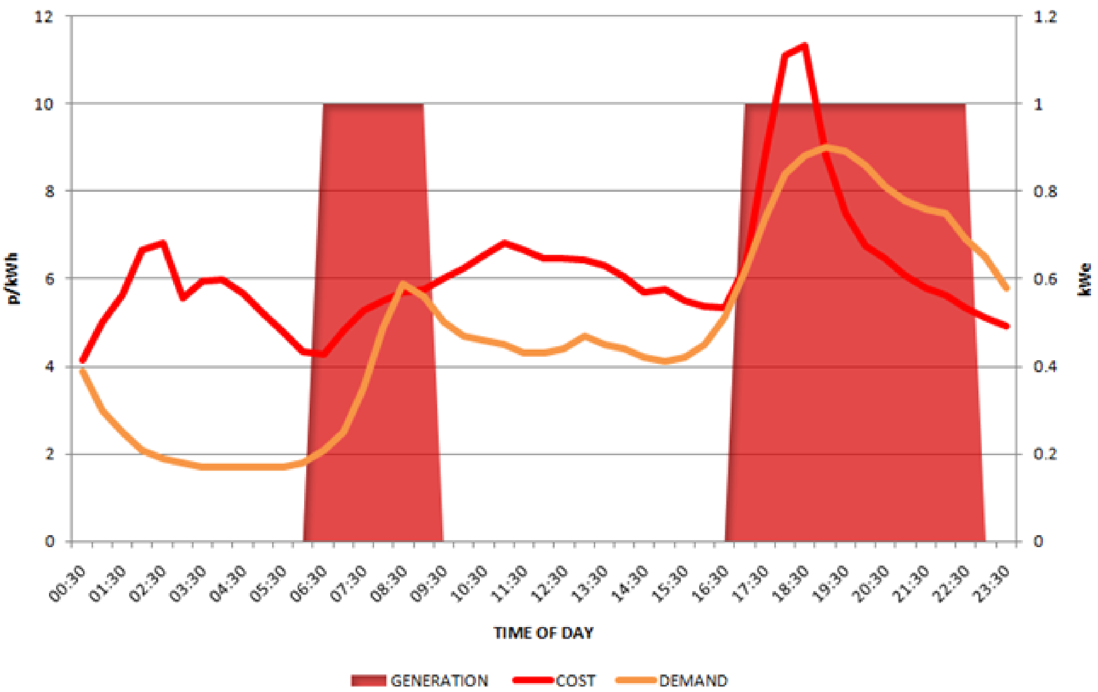
Which technology is able to deliver the most significant carbon emissions reduction in the domestic heat sector now and for the next decade at least? If we consider replacing the current 20 million or so gas central heating boilers in the UK with a lower carbon alternative, which technology is likely to have the most significant immediate impact?

Replacing an ageing gas boiler with a modern condensing boiler will certainly make a major impact, but let us now assume that we take that high efficiency boiler as our baseline to assess the benefit of further incremental investment. Compared with a condensing boiler, an engine based micro CHP unit could save 1.7 tonnes CO_2 annually for a typical family home, whereas an SOFC (Solid Oxide Fuel Cell) could save more than 4 tonnes CO_2 as discussed below. A heat pump with an SPF (Seasonal Performance Factor)[12] of 3 fuelled by electricity with a carbon intensity of 0.67kgCO_2/kWh would deliver heat at a carbon intensity of 0.22kgCO_2/kWh, exactly the same as for a gas boiler with natural gas at 0.194kgCO_2/kWh and 90% system efficiency; no reduction in carbon emissions would be achieved. Anything less than an SPF of 3 and the heat pump will be responsible for increasing carbon emissions[13].

So, wherever natural gas is available micro CHP offers clear benefits over a heat pump given current grid mix. However, where a household does not have access to the natural gas grid, the displacement of oil or other relatively high carbon fuels does offer significant potential for carbon savings, although such homes represent a very small minority of UK homes. We also need to acknowledge that both the grid mix and the performance of heat pumps should evolve to show heat pumps in a more favourable light in due course and we should therefore continually re-evaluate the relative merits of these technologies.

Both in UK and European government circles, there is a widely held, but erroneous, belief that we must choose between policies supporting micro CHP and heat pumps as though they were mutually exclusive domestic heating strategies. The reality is that the widespread introduction of heat pumps, a heat-led electricity *consuming* technology today would give rise to adverse impacts on both our carbon emissions and security of supply, both of which can be mitigated by the parallel introduction of micro CHP, a heat-led, electricity *generating* technology.

FIGURE 1: GRAPH OF DIVERSIFIED ELECTRICITY DEMAND AND MICRO CHP OPERATION



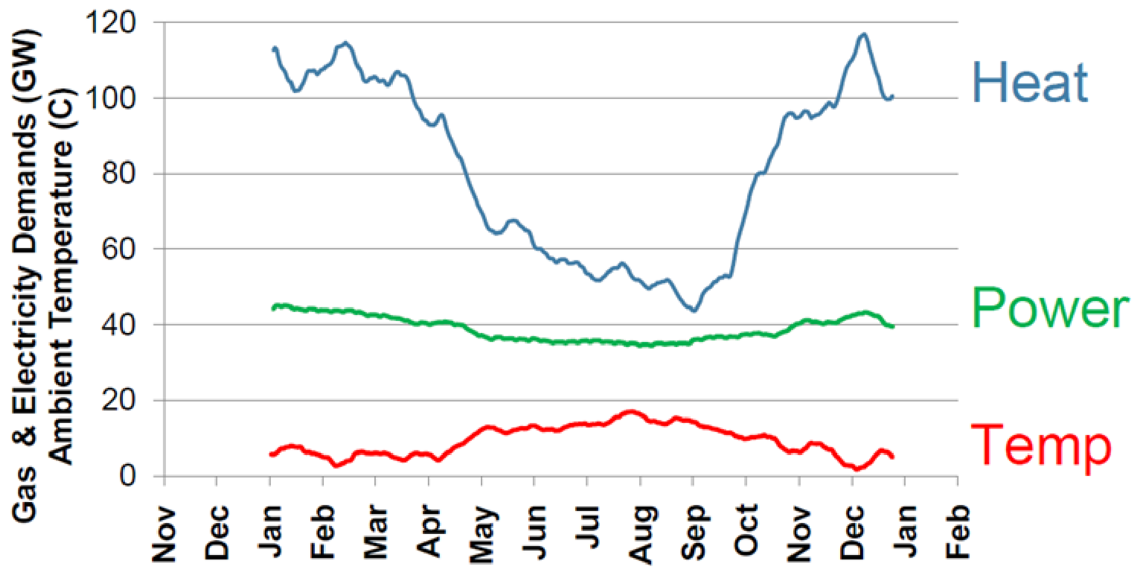
Electrical demand in the UK tends to peak during winter evenings as shown in the demand curve for a typical winter day; this will be exacerbated by any additional demand from electric heat pumps which will inevitably respond to programmed domestic heating schedules as shown in the shaded periods. During those same peak periods, micro CHP will also operate to deliver domestic heat and will provide valuable electricity as a by-product to support the demand from heat pumps.

In the longer term, there is little doubt that electric heat pumps which are able to deliver SPF of 3 and above may provide a very efficient and low carbon heating solution where supplied with low carbon electricity. However, for the time being, the relatively high carbon intensity of the UK electricity supply means that they are not able to reduce carbon emissions when compared with natural gas central heating systems.

Furthermore, the increasing electrical demand on the low voltage network resulting from the introduction of heat pumps to displace gas boilers will impose a substantial burden not only on central generating plant capacity, but also on the local distribution network delivering that energy.

Today, 85% of energy use in the home is for space and water heating[14]. If heat pumps are to provide this heat, even with optimistic assumptions as to their performance in the UK housing stock[15], this would result in a doubling of domestic electrical energy demand, ignoring any increase for electric vehicle charging. The winter peak capacity demand and the resulting generation and distribution impacts would be even higher as heat pumps tend to perform less efficiently as ambient temperatures fall.

FIGURE 2: GRAPH OF ELECTRICITY AND HEAT ANNUAL PROFILE



This graph of daily mean heat and power demands shows, as would be expected, a clear correlation between ambient temperature and heat demand. Assuming this heat demand is to be met from electric heat pumps with a SPF of 3, an additional electrical capacity of around 40GWe would be required, doubling the current demand.

Source: Energy Technologies Institute

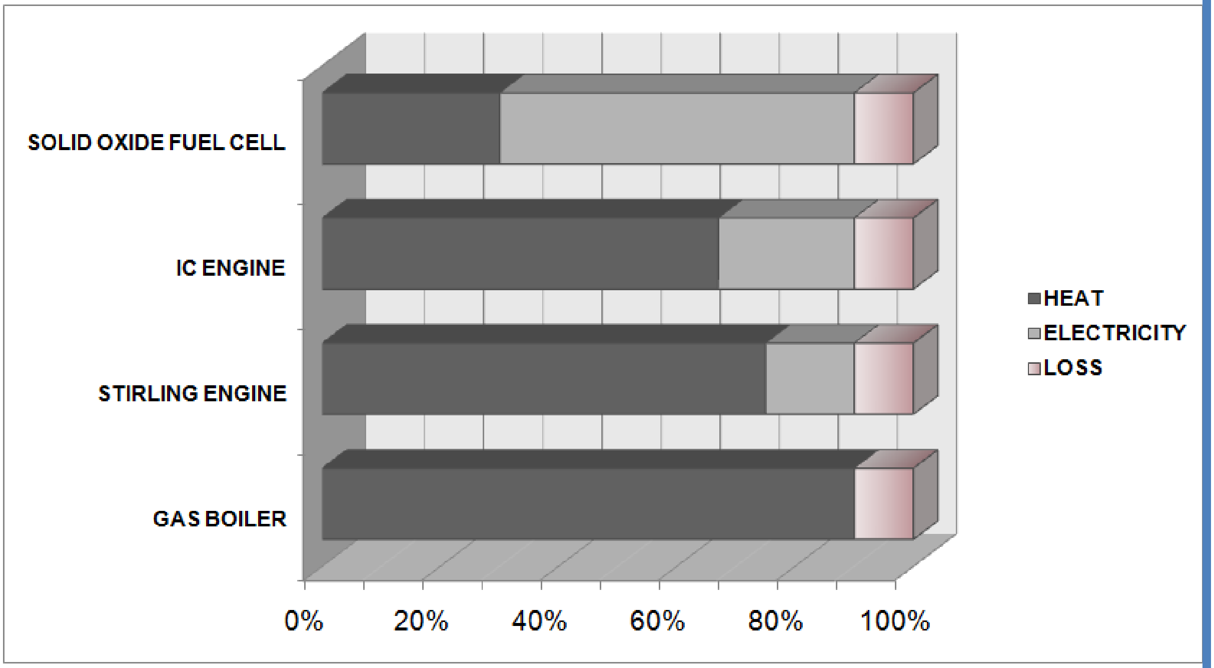
In this context, micro CHP which provides low carbon electricity and extends the life of our finite fossil fuel resources, complements the simultaneous incremental introduction of heat pumps which will become increasingly beneficial as the grid decarbonises. Indeed, micro CHP of all technologies is ideally suited to this role of supporting the widespread introduction of heat pumps, as it generates power at or near the point of increased electrical demand from those heat pumps, notably within the low voltage distribution network, thus simultaneously overcoming generation and distribution constraints. Also, being a heat led technology, micro CHP tends to generate at a time when electrical demand from the heat pumps, which are by definition heat led, is highest.

Micro CHP and decarbonisation of the UK electricity supply

The environmental value of micro CHP lies in its ability to provide electricity (which has a high exergy value) for the "cost" of the heat which would otherwise have been produced from a given amount of primary energy (fuel) input. In the UK at present the CO_2 saving from the displaced electricity is generally taken to be around 0.568 $kgCO_2/kWh$[16]. Compared with the lost "opportunity cost" of the heat which could have been produced by a high efficiency (90%) gas boiler, of 0.22 $kgCO_2/kWh$, this results in a CO_2 saving of 0.346 $kgCO_2/kWh$ (= 0.568 – 0.22 $kgCO_2/kWh$) for every unit of electricity produced by the micro CHP system. This is regardless of the electrical conversion efficiency of the device, as long as the total conversion efficiency is equal to that of the gas boiler (90%). The benefit of higher electrical efficiency is that more electrical energy is produced for any given heat load; that is, for any given installation, the total CO_2 savings are proportional to the electrical efficiency. Thus, for a typical 1kWe Stirling engine micro CHP unit generating 3000kWh annually the carbon displaced would be just over 1 tonne, whereas a SOFC (Solid Oxide Fuel Cell) running continuously would produce 8760kWh saving over 3 tonnes of carbon dioxide each year.

However, as the electricity produced by the overall generation mix reduces, so does this marginal benefit, so it could be argued that when the grid CO_2 mix reduces to 0.22$kgCO_2/kWh$, there will be no environmental benefit from operating micro CHP. A similar argument may, incidentally, be applied to the generation of electricity from other microgeneration sources such as solar photovoltaics where the high embodied carbon leads to significantly higher specific CO_2 emissions than is the case for micro CHP. In that case also, there comes a point at which, based on displacement of average grid mix, the microgeneration source would appear to actually increase global carbon emissions. This, however, is a rather simplistic assumption and takes no account either of distribution losses between remote central generating plant and the consumer which result in higher effective CO_2 at the point of demand than at the point of generation nor, more importantly, of different forms of microgeneration and even different forms of micro CHP which generate with differing profiles (e.g. SOFC is baseload, Stirling is substantially peak following). And so it is not the average grid supply which is displaced, but a weighted value based on the marginal plant operating at the time the micro CHP unit is operating over the entire year, or indeed its entire life.

FIGURE 3: SIMPLIFIED DIAGRAM OF CARBON DISPLACEMENT BY MICRO CHP



Assuming the total efficiency of the micro CHP system is the same as for a gas boiler, the value in economic and environmental terms is the difference between the value of heat and the value of electricity.

Numerous studies have shown that the "long term" carbon intensity figure used in policy of 0.43 $kgCO_2/kWh$ is inaccurate as an average figure at the power station today. The average displaced CO_2 at the power station is around 0.5 $kgCO_2/kWh$ and the more important marginal displaced figure is, according to Hawkes, 0.69 $kgCO_2/kWh$[17]; taking grid losses into account, this figure needs to be increased by around 7% for supply to the home[18]. Hawkes' analysis also contends that the "peak marginal" emissions, that is the emissions from marginal plant during the peak hours during which micro CHP operates, are virtually the same as the "average marginal" emissions. However, this analysis is based on operating regimes derived from the interim results of the Carbon Trust micro CHP field trials which included a preponderance of homes equipped with primary thermal storage which, in the absence of any economic or system drivers to the contrary, were not optimised to displace maximum carbon emissions.

(This, incidentally, raises an important issue regarding the need for an industry framework which attributes value appropriately to encourage householders to operate their microgeneration systems for the optimum benefit of the energy system as a whole and is discussed further elsewhere[19].)

Earlier analysis undertaken by Ilex[20] showed that for a typical Stirling engine micro CHP system responding directly to thermal demand, actual displaced emissions were around 10% higher than for simple marginal emissions averaged over the whole year, which of course includes emissions during summer when central plant tends to have significantly lower emissions due to the lower system demand and when micro CHP operates only a few hours daily to provide DHW. Taken together, these two studies imply a displaced carbon figure for heat led micro CHP of around 0.74 kgCO_2/kWh generated and around 0.80 kgCO_2/kWh for electricity delivered to the home, compared to 0.67 kgCO_2/kWh and 0.74 kgCO_2/kWh for SOFC or other baseload micro CHP technologies.

Accordingly, the net carbon benefit of heat led micro CHP is 0.80-0.22 = 0.58 kgCO_2/kWh assuming the current carbon intensity of both gas and electricity supplies; the annual carbon saving is revised to 1.7 tonnes. However, for SOFC operating baseload, the average marginal figure is more appropriate so that, although the savings still increase, it is by a lesser amount resulting in a total annual saving of 4.3 tonnes.

According to National Grid[21], up to 18% of our current natural gas consumption could in future be derived from renewable gas, even without the inclusion of bio-methane derived from crops. This is equivalent to around 50% of residential gas demand. It is not inconceivable therefore that as the electricity grid decarbonises due to the introduction of large scale renewables, so the gas grid could do exactly the same, particularly in a scenario where excess intermittent renewable electricity is used to produce hydrogen for injection into the gas grid.

However, proposing solutions predicated on the total decarbonisation of either gas or electricity tends to lead to perverse proposals such as the advocacy of electric resistance heating which is now magically "zero carbon". As decarbonisation of both electricity and gas will only be achieved at considerable cost, it is desirable that each will be utilised as efficiently as possible and, in this context, it may be that bivalent domestic heating systems comprising electric heat pumps and micro CHP become an effective means of utilising renewable electricity when available and using high value renewable gas as a means of dispersed back-up.

FIGURE 4: TABLE OF AVERAGE & MARGINAL CARBON DIOXIDE EMISSIONS

	kgCO2/ kWh	NET SAVING	ANNUAL SAVING (kgCO2)	ANNUAL SAVING (kgCO2)
			3000kWh	8760kWh
UK AVERAGE (ASSUMED POLICY VALUE)	0.43	0.21	630	1840
SAP 2005	0.57	0.35	1044	3048
ACTUAL UK AVERAGE 2009	0.51	0.29	870	2540
AVERAGE MARGINAL	0.69	0.47	1410	4117
PEAK MARGINAL	0.74	0.52	1560	4555
AVERAGE MARGINAL PLUS LOSSES	0.74	0.52	1560	4555
PEAK MARGINAL PLUS LOSSES	0.80	0.58	1740	5081

Table showing specific carbon dioxide in electricity production by central plant as well as impact of assumed grid mix on displaced carbon benefit from SOFC micro CHP (red) and Stirling engine micro CHP (green).

Security of Supply; backing up large scale intermittent renewables

As stated earlier, technologies within the overall generation mix, including micro CHP, cannot be considered in isolation; each is a component of an overall system with potential conflicts and synergies with other components of the generation portfolio. For example, as outlined in an ECI paper[22], micro CHP supports the operation of intermittent wind so that, in that albeit limited scenario, it is necessary to consider the overall sum of wind plus back up plant, compared with wind plus micro CHP and a very much smaller amount of back up plant.

In this context, no-one suggests that there will be no back up gas fired plant operating to support large scale wind for the foreseeable future, even though the specific CO_2 emissions from the most efficient CCGT are well in excess of 0.32 $kgCO_2/kWh$. Indeed it is the availability of flexible (high carbon at around 0.41 $kgCO_2/kWh$) OCGT generation for short periods which may facilitate the introduction of large scale intermittent near zero carbon generation; simply put, it is only possible to achieve a low carbon energy system by accepting some compromise at certain points in that system, at least for several decades to come[23].

Conclusions

Within the context of an energy system evolving from our current high carbon electricity system based largely on fossil fuel generation, to a sustainable low carbon system, it is probable that micro CHP will have a key role to play for several decades, both in terms of providing security of supply in support of a gradual electrification of the heat and personal transport sectors, and as a carbon mitigating technology with or without the decarbonisation of the gas grid.

It is also quite likely that micro CHP will continue to play a role on a permanent basis as an element of a bivalent energy system to optimise the performance of domestic heating systems dependent on the availability of low carbon intermittent renewable electricity generation.

Notes & References

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[1] The IEA MARKAL model was used to produce the 2007 Energy White Paper marginal abatement cost curve which simply aggregated all electricity producing microgeneration technologies, so that micro CHP was considered as synonymous with solar photovoltaics.

[2] *Renewable Energy Review*, UK Climate Change Committee, May 2011

[3] Although it is possible to modulate the output of current EPR reactors down to around 25% nominal power, they cannot be completely turned off without significant impact on maintenance and operating costs. It is understood that the UK regulator's concerns regarding the additional safety risks of modulating output mean that they may not in any case be licensed to operate in this mode. It is also often overlooked that the proposed 1.6GWe EPR will itself require an increase in back up capacity in the form of circulating reserve from the current 1.2GW to 1.6GW, involving additional fossil fuel burn and increasing carbon emissions.

[4] Vincent de Rivaz CEO EdF reported in www.ft.com 26 May 2009

[5] In the UK approximately 1.5 million gas boilers are replaced every year. If each of these were to be replaced by a 1kWe micro CHP unit, this would result in a generating capacity equivalent to an additional 1.5GWe annually.

[6] Paul Golby, CEO E.ON UK June 2008 reported in The Telegraph

[7] The CCC Review alludes to a requirement for gas fired back-up capacity, but just as the technical potential of modulating CCS and nuclear may be over-ridden by the need to recover high investment costs as soon as possible by running baseload, so it is difficult to imagine companies investing in new, high efficiency back-up plants which are constrained to operating very few hours. It is for this reason that more holistic solutions such as consideration of distributed assets (including micro CHP) should be included in any sustainable energy system.

[8] *UK power generation & the growing gap in firm capacity*, Hugh Sharman, Institution of Civil Engineers, September 2007

[9] Clean Air Act of 1956

[10] *Denmark: Key Developer of Climate Solutions*, Ministry of Foreign Affairs of Denmark, November 2008

[11] *Building a roadmap for heat; 2050 scenarios and heat delivery in the UK*, CHPA 2010

[12] SPF is the ratio of electrical energy input to the heat pump compared with the useful heat delivered to the home over the course of a year taking account of system losses and parasitic loads.

[13] *Options for Low-Carbon Power Sector Flexibility to 2050*, Pöyry, 2010 puts forward the view that waiting until the electricity system is flexible enough to accommodate heat pumps would "lock out" this technology. As both micro CHP and air source heat pumps are expected to be replaced on a 19 year cycle this is clearly not the case.

[14] BRE Domestic Energy Fact File

[15] The EST field trial showed the majority of systems achieving COP of between 2 and 2.5; assuming that SPF of 3 can be achieved, the 85% heat figure would result in around 30% electricity, double the existing 15% currently used for lighting, cooking etc.

[16] Figure used in SAP (Standard Assessment Procedure) 2005 as basis for calculating carbon emissions for Building Regulations purposes.

[17] *Estimating marginal CO2 emissions rates for national electricity systems*, A.D. Hawkes Energy Policy 38, June 2010

[18]*Electricity System Distribution Losses* report by Sohn Associates for OFGEM, 2009

[19] *Microgeneration and Billing*, CRM, Billing & Metering Conference, Amsterdam, Jeremy Harrison, 2008

[20] *Carbon displacement by micro CHP generation*, Ilex Energy Consulting, 2004

[21]*The potential for Renewable Gas in the UK*, Ernst & Young for National Grid, January 2009

22 *The practicalities of Developing Renewable Energy Standby Capacity and Intermittency*, Environmental Change Institute, Graham Sinden, 2004

23 It is possible that in the longer term, advanced DSM can match demand to available capacity and that the introduction of complementary technologies such as vehicle to grid may reduce the necessity for back up plant.