Zero Carbon Infinite COP Heat from Fuel Cell CHP

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Originally published in Applied Energy, Elsevier B.V.

http://dx.doi.org/10.1016/j.apenergy.2015.02.089

Abstract

Fuel cells are a promising technology for combined heat and power (CHP); however their efficiency and carbon benefits are often overlooked because of their reliance on fossil fuels. This paper sets out the numerical methods and evidence of real-world performance needed to compare fuel cells with other low-carbon technologies. It is demonstrated that firstly, the efficiency of present-day fuel cells is high enough to outperform the best electric heat pumps, even when these are powered exclusively by the best modern power stations. The equivalent COP (coefficient of performance) of today's fuel cells ranges from 5 to ∞, compared to 3–4 for the best ground source heat pumps. Secondly, this high efficiency means that even when fuelled with natural gas, the heat from a fuel cell is zero- or even negative-carbon when electricity from central power stations is displaced.

Highlights:

- Fuel cells are becoming widely used for residential and commercial heating
- They offer a low-carbon alternative to the all-electric heat pump future
- Fuel cells are more efficient than the best heat pumps with equivalent COPs over 5
- Even on natural gas, fuel cell heat can be zero carbon due to displaced electricity

Keywords: fuel cells; CHP; heat pumps; buildings; heat; carbon emissions;

1 Introduction

Fuel cell combined heat and power (CHP) is the most efficient and low-carbon means of providing heat and power to buildings. However, it is generally overlooked in energy roadmaps as the debate on sustainable heat narrows around heat pumps powered by low carbon electricity [1, 2]. The prevailing view is an intuitive one: because fuel cells consume natural gas, they can only be a bridging technology – a stepping stone on the route to 'truly' sustainable heat and power [3, 4].

This paper aims to challenge this opinion by developing simple and robust means for comparing the efficiency and carbon emissions of fuel cells against those of competing technologies: CHP engines, electric and gas heat pumps. A wealth of previous studies consider the carbon savings from these technologies (e.g. [5-9], [10-14], [15-18]), but do so in isolation. Those that provide a comparison between technologies rely on high-level generalisations [2, 19-21] or numerical simulations for performance and building load [22-25], which cannot capture the real-world challenges and diversity of operation in buildings. This paper collates the latest data on technology performance to supersede theory with empirical field data. The focus is placed on fuel cells as these have the most limited operating experience to date.

Previous studies that compare CHP with heat pumps do so in terms of the annual carbon or cost saving, which is highly specific to the country and building being considered. This paper develops two novel and more general methods of comparison: the equivalent coefficient of performance (COP), which has not before been applied to fuel cells; and the carbon intensity of heat, which is widely overlooked compared with that of electricity. These metrics can be translated to other countries and technologies without recalculation, and are used to show that fuel cells deliver heat with higher efficiency than the best heat pumps, and that this heat can justifiably be classified as zero- or even negative-carbon.

The leading fuel cell CHP technologies and their applications are first introduced, then section 2 characterises their technical performance. Section 3 develops the methods for comparing efficiency and carbon emissions across technologies. Section 4 calculates the equivalent coefficient of performance (COP) and carbon intensity of fuel cells, demonstrating their carbon impact in the UK. Section 5 concludes by discussing the rationale for and merits of classifying fuel cells as a zero-carbon technology.

1.1 Fuel Cell Technologies

Fuel cells have been under development for 50 years, but failed attempts at commercialisation and over-confident market analysts have left the impression that fuel cells are "forever 5 years away" [26]. Although prototype hydrogen vehicles command greater media attention, CHP is the largest and most established market for fuel cells. In 2009 manufacturers progressed beyond demonstration projects to begin selling thousands of systems per year, marking the long-awaited transition towards mass production. By 2015, residential fuel cells will be sold without subsidy in Japan, finally reaching the status of commercial viability.

Fuel cells convert chemical energy into electrical current and heat without combustion. A simplified view of a fuel cell is a cross between a battery (an electrochemical converter) and a heat engine (a continuously fuelled, air breathing device) [6]. At its heart lies the fuel cell stack: a set of individual cells stacked together to provide greater power, much like cells in a battery. The stack produces the core conversion of hydrogen into electricity, and must be surrounded with several ancillary systems to form a complete CHP system:

- A fuel processor to convert natural gas or other fuels into hydrogen;
- Heat recovery systems to produce hot water;
- An inverter and power conditioner to provide grid-synchronised AC;
- A backup gas boiler to meet peak heat demand;
- Control and safety systems, etc.

Most stationary fuel cells run on natural gas due to its availability and low cost. Systems can also run on liquid petroleum gas (LPG), kerosene, and renewable sources such as landfill and sewer gas. If hydrogen were readily available, fuel cells could bypass hydrocarbons completely, giving several benefits:

- Halving system complexity and cost by eliminating the fuel processor [27];
- Improving efficiency by 15–20% [28];
- Elevating fuel cells from transition-technology to being seen as core part of low-carbon energy systems.

Just as there are different types of battery, many fuel cell technologies exist, using different materials and operating temperatures. This affects the fuels they tolerate and the peripheral equipment they require; however, they all share the characteristics of high efficiency, few moving parts, quiet operation, and low emissions. The four most common fuel cell technologies for CHP are examined below.

1.1.1 PEMFC – Proton Exchange Membrane Fuel Cells

PEM is the most developed technology, powering ~90% of fuel cell CHP systems [29]. A decade of R&D has yielded high efficiency and durability, while costs have fallen rapidly due to mass production [27].

Thin polymer sheets are used for electrolyte, which conduct ions at room temperature. The low operating temperature (0–100°C) means precious metal catalysts (e.g. platinum) are required [30]. This is often cited as a cost concern, but metal loadings are very low, around 0.1–0.2 grams per kW (£3–6). However, platinum imposes strict fuel purity requirements as it is easily poisoned by sulphur and carbon monoxide. Extensive fuel processing is required for fossil fuels, and humidification as polymer electrolytes only conduct when moist.

Current research is aimed at system simplification: removing the platinum could avoid these complex engineering solutions [31], while high-temperature PEM can operate on dry hydrogen over 100°C removing the need for humidifiers [32].

1.1.2 SOFC – Solid Oxide Fuel Cells

High-temperature SOFCs are used in residential and large industrial CHP systems, and have recently grown to reach 10% of global sales [29]. SOFCs benefit from the highest electrical efficiency and greater fuel-flexibility, but they cannot be operated as dynamically as PEMFCs due to their high operating temperature (500–1000°C) [33]. Start-up and shut-down are sensitive operations taking 12 hours or more, meaning systems tend to run "always-hot".

SOFCs use thin ceramic electrolytes which only conduct ions when hot. High temperature operation allows cheaper catalysts such as nickel and lanthanum to be used in place of platinum, but means that all components must withstand extreme thermal stresses. Non-noble catalysts are more tolerant to impurities so fuel processing is simpler, and some SOFCs can use desulphurised methane directly as fuel [34].

Fundamental research targets durability and thermal stability, with a trend towards intermediate temperatures (500–750°C) [35]. This allows a wider range of materials to be used, lowering costs and improving dynamic performance.

1.1.3 MCFC – Molten Carbonate Fuel Cells

High-temperature MCFCs are used in industrial CHP and grid-scale electricity production (3–60 MW), and recently became the market leader for large stationary applications [29]. MCFC benefit from relatively low cost due to non-platinum catalysts and simpler ancillary systems, but suffer from low lifetime and power density [36].

Molten lithium and potassium carbonate electrolyte is suspended in a ceramic matrix which must be permanently heated to 650°C to avoid damage from solidification. Low-cost nickel catalysts work as the stack runs at high temperature, meaning that natural gas and other hydrocarbons can be internally reformed as in SOFCs. Uniquely, MCFCs require carbon dioxide in the fuel stream, which is recycled from the anode.

Manufacturers aim to double lifetime through further research into electrolyte stability, and improve power density to reduce cell size and thus material costs [37, 38].

1.1.4 PAFC – Phosphoric Acid Fuel Cells

PAFCs were the first fuel cell technology employed for heating, being used since the 1970s in commercial-scale CHP systems [39]. The industry has remained stable for decades, with just two manufacturers and 20–50 systems sold per year [29].

Liquid phosphoric acid at 180–250°C forms the electrolyte, with platinum catalysts at 40 times the loading of PEMFC (7.5 g/kW) [40]. Platinum introduces similar constraints on fuel purity to PEMFCs, and contributes 10–15% of system cost, meaning cost reduction is the highest priority for manufacturers. PAFCs benefit from long lifetimes and high reliability, but slightly lower efficiency than other technologies [28].

1.2 Applications and International Status

Fuel cells are modular and easily scale up from serving individual homes to office blocks and industrial complexes. With combined heat and power (CHP) systems, heat produced by the fuel cell's reactions is captured and delivered to the building. CHP (also known as cogeneration) can therefore provide exceptionally high efficiencies (up to 95%), and reduce dependence on central generation, saving on electricity costs and carbon emissions.

1.2.1 Residential CHP

In temperate climates houses are a nation's largest consumer of heat. The UK's 26 million houses consume 375 TWh per year, half the national total [41]. While the average UK household demands 15 MWh of heat per year, the largest demand 6 times more than the smallest, and demand is highly seasonal, peaking in winter at 7 times the summer level, as shown in Figure 1.

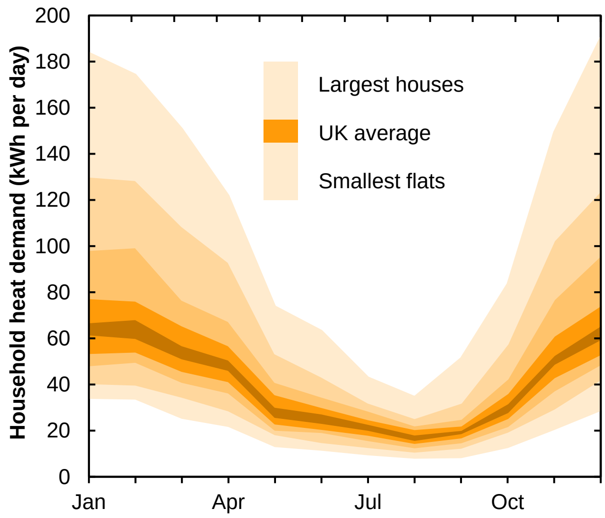

Figure 1: Variation in UK household heat demand (space plus water) for an average weather year [28].

Fuel cells are best suited to larger properties with sufficient physical space for installation and greater heat demand. Condensing gas boilers are the main competition: small, wall-hung units delivering 15–40 kW of heat.

Residential fuel cells are packaged as complete heating systems, with a 0.75–2 kW electric (1–2 kW thermal) PEMFC or SOFC stack integrated with a boiler and hot water tank, to remain compatible with the growing number of houses with combi-boilers and no heat storage. Fuel cells are physically larger than gas boilers, typically floor-standing units the size of a large fridge-freezer that are installed outside or in basements, as in Figure 2. These weigh 150–250 kg and occupy 2m², including the hot water tank and supplementary boiler [42, 43], although smaller wall-hanging models are under development.

Residential micro-CHP has rapidly expanded since the 2009 launch in Japan. In 2012 fuel cells outsold engine-based micro-CHP systems for the first time, with 28,000 sales worldwide [44]. Leading manufacturers include Panasonic, Toshiba, Sanyo and Kyocera; CFCL; Baxi, Viessmann and Hexis; GS and FCPower. Recently, Japanese manufacturers have partnered with German heating companies for expansion into Europe (e.g. Panasonic and Viessmann, Bosch and Aisin Seiki [45]).

Figure 2: Photos of the Panasonic EneFarm residential PEMFC (left) and ClearEdge PureCell commercial PAFC (right).

Japan leads global deployment with 60,000 systems sold in the last four years [46]. This is 6–8 years ahead of South Korea and Europe; however, all regional markets are roughly doubling each year, as shown in Figure 3. This growth is expected to continue: the Japanese government targets 1.4 million fuel cells installed by 2020, and Europe targets 50,000, predominantly in Germany [46, 47].

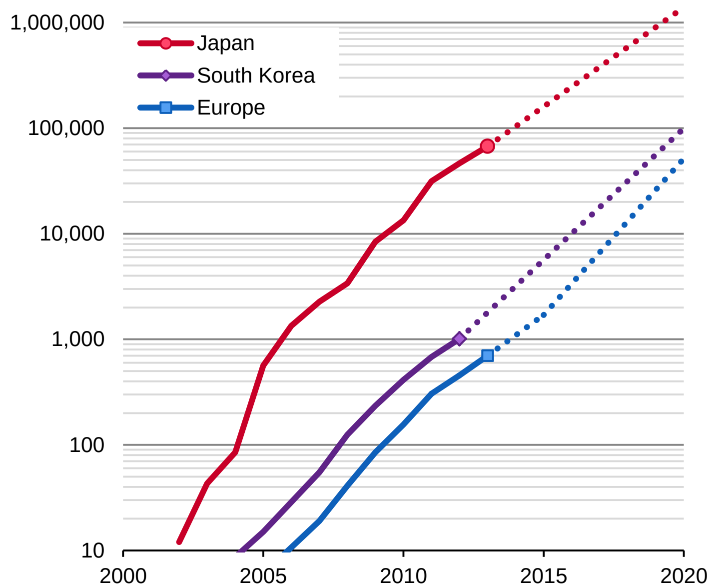

Figure 3: Cumulative number of fuel cell micro-CHP systems, showing historic growth of PEMFC and SOFC combined (solid lines) and near-term projections (dotted lines) [48].

1.2.2 Commercial CHP

Shops, offices, hospitals and other tertiary-sector buildings provide another significant market for fuel cells, consuming around 20% of national heat demand [1, 49]. Large premises tend to have more steady demand profiles than individual homes, and so are better suited to fuel cells. Low upfront cost, reliability and physical size are high priorities.

Gas is the predominant fuel, burnt in large commercial boilers (50–300 kW_{th}) which are installed in parallel to meet peak load. High-efficiency condensing models are available, but are not legally mandated as they are in the UK's residential sector.

Commercial fuel cells range from 100–400 kW electrical, and typically operate in parallel with existing heating systems. They are larger than conventional boilers: a 400 kW system occupies 22–36 m^2 and weighs 30–35 tonnes [50, 51], meaning 1 to 2 MW can be installed into the area of a tennis court.

Around 400 PAFCs (~85 MW) from ClearEdge and Fuji operate in the US, Germany, Japan and Korea [52, 53]. Multi-MW MCFCs have recently taken off, with 200 MW installed by FuelCell Energy and POSCO since 2011 [29]. Large PEMFC and SOFC systems also exist – for example Bloom Energy produce power-only SOFCs, but these fail to utilise the cogeneration benefits of CHP.

1.2.3 Heat Networks

Large fuel cells can used for district heating, either within a single apartment block or a wider heat network. This is more cost effective than using many individual residential and commercial systems, as capital cost per kW falls with capacity, and having many end-users gives a smoother demand profile and thus higher utilisation. The UK's potential is limited as district heating is not widely used at present [1].

1.2.4 Industrial Heat

Around a third of heat demand comes from industry, mostly concentrated into large manufacturing facilities [49, 54]. A mix of solid fuels, natural gas and electricity is used, making industrial heat around a third more carbon-intensive than other sectors [1, 49, 54]. Uniquely, more than half of demand is for high-grade process heat (over 500°C) predominantly in iron and steel, cement, glass and chemicals [54]. Individual facilities have specific requirements for the quantity and temperature of heat delivered, making this a challenging sector for generic solutions.

Low-grade industrial heat is a large and untapped market that fuel cells could move into, providing heat at up to 120°C (PAFC) and 200°C (MCFC) [50, 51]. SOFCs provide heat at up to 1000°C and so could decarbonise a wider range of industrial facilities, if they became cost competitive with CHP engines.

2 Data

2.1 Technical Performance of Fuel Cells

The technical characteristics and performance of each fuel cell technology are summarised in Table 1. All efficiencies are expressed against LHV; these can be converted to HHV by dividing by 1.109 (for natural gas).

Table 1: At-a-glance summary of fuel cell performance.

		PEMFC	SOFC	PAFC	MCFC
Application		Residential		Commercial	
Electrical capacity	(kW)	0.75–2		100–400	300+
Thermal capacity	(kW)	0.75–2		110–450	450+
Electrical efficiency*	(LHV)	35–39%	45–60%	42%	47%
Thermal efficiency*	(LHV)	55%	30–45%	48%	43%
System Lifetime	'000 hours years	60–80 10	20–90 3–10	80–130 15–20‡	20 10‡
Degradation rate†	Per year	1%	1–2.5%	0.5%	1.5%

** Rated specifications when new, which are slightly higher than the averages experienced in practice*

† Loss of peak power and efficiency

‡ Includes overhaul of the fuel cell stack half-way through life

2.1.1 Operating Efficiency

Both electrical and total efficiency are relevant for CHP systems, but electrical efficiency is the main focus as power is the more valuable output. Fuel cells offer the highest electrical efficiency of any CHP technology, and even small micro-CHP fuel cells rival even the best conventional power stations [6].

The leading SOFC systems at residential and larger scales have rated electrical efficiencies of 45–60%, and total efficiencies of 85–90% [7, 55]. Fuel processing for PEMFCs incurs greater losses so electrical efficiencies are lower (up to 39%) but total efficiencies are higher (95%) [8, 43]. European residential systems lag behind the leading Japanese and Australian models, with current SOFC and PEMFCs limited to 30–35% electrical efficiency [42].

Large PAFCs are rated at 42% electrical / 90% total efficiency [50], while MCFCs are rated at 47% / 90% [51]. Electrical efficiency decreases over lifetime due to degradation (see 2.1.4), giving lifetime-average efficiencies of 39% for PAFCs and 42% for MCFCs; whilst total efficiency remains stable [56, 57]. Field performance is consistent with these specifications as commercial buildings provide more constant demand for energy.

In real homes, the efficiency of small PEMFC and SOFC systems is lower than in laboratory tests due to electricity consumed by auxiliary systems, reduced part-load efficiency, energy for start-up cycles, and dumping excess heat during summer [28, 42]. A general trend is that higher efficiencies are achieved in houses with higher heat demand [58, 59]. CHP engines and heat pumps experience similar penalties in residential usage due to non-ideal operating conditions [13, 60, 61].

Table 2 summarises the efficiency of 11 residential fuel cells, giving 'real-world' efficiency from demonstrations (where known) alongside manufacturers' specifications. This reveals that the performance gap is around one-tenth of rated efficiency.

Table 2: Comparison of electrical and total efficiencies specified by fuel cell manufacturers and achieved in real-world field demonstrations.

			Rated Specifications*	Field Performance†	Real-world performance gap
PEMFC	Panasonic & Toshiba (EneFarm) [28, 58, 62-64].	2014	38.5–39%$_{el}$ / 94–95%$_{tot}$	?	–
PEMFC	Panasonic & Toshiba (EneFarm) [28, 58, 62-64].	2010	35–37%$_{el}$ / 81–89%$_{tot}$	32.1%$_{el}$ / 73.2%$_{tot}$	8–13%
PEMFC	GS, FCPower & Samsung [65]	2012	34–36%$_{el}$ / 82–86%$_{tot}$	?	–
	Vaillant, Baxi & Hexis‡ [42, 66]	2012	31–35%$_{el}$ / 90–96%$_{tot}$	30.5%$_{el}$ / 88.0%$_{tot}$	8–9%
	Vaillant, Baxi & Hexis‡ [42, 66]	2009	26–32%$_{el}$ / 90–96%$_{tot}$	24.2%$_{el}$ / 84.1%$_{tot}$	16%
SOFC	Aisin Seiki & JX (EneFarm-S) [64, 67-69]	2014	43–46.5%$_{el}$ / 87–90%$_{tot}$	?	–
SOFC	Aisin Seiki & JX (EneFarm-S) [64, 67-69]	2011	42–45%$_{el}$ / 77–85%$_{tot}$	40.0%$_{el}$ / 82.1%$_{tot}$	5–12%
SOFC	CFCL [7, 70]	2011	60%$_{el}$ / 85%$_{tot}$	51–56%$_{el}$	7–15%

** Electrical and total efficiency referred to as %$_{el}$ and %$_{tot}$, against LHV.*

† Referred to as "utilisation efficiency" or "capacity factor" to distinguish from gross generating efficiency under ideal laboratory conditions.

‡ Data is only available aggregated over three manufacturers of both PEMFC and SOFC.

Fuel cells are credited with very high part-load efficiency as stack voltage rises with decreasing current density. In complete systems this is outweighed by parasitic losses, so efficiency falls off as a rational function, as in Figure 4. The performance differs by stack type: electrical efficiency declines more rapidly for SOFCs, yet thermal efficiency increases at part-load.

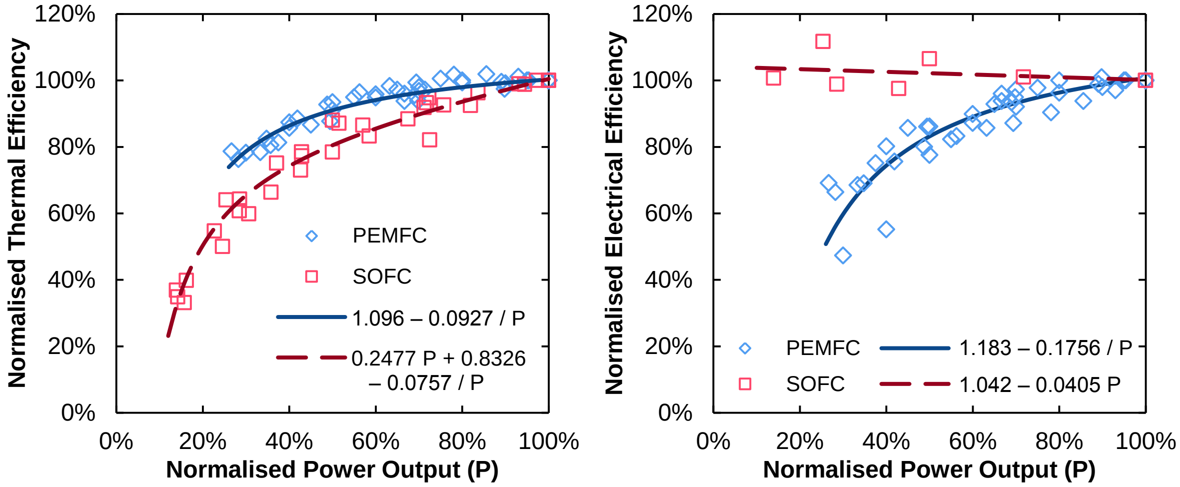

Figure 4: Electrical and thermal efficiency of residential CHP systems against power output, normalised against each system's efficiency at full power. Data from 8 PEMFC and 6 SOFC systems [28, 62, 67, 71].

2.1.2 System Lifetime

Durability was a key issue holding fuel cells back as lifetimes were well below the critical milestone of 40,000 hours – around 10 years of residential operation (5,000 hours per year) [28]. Recent improvements have been substantial: Japanese PEMFCs are now guaranteed for 60–80,000 hours [8, 43], and SOFCs for up to 90,000 hours [55]. European and other residential systems are catching up to these standards, with lifetimes currently at 10–20,000 hours [42, 72].

Figure 5 charts the improvement in system lifetimes based on manufacturers' guarantees and field results. Exponential curves are fitted to each technology, which suggests that industry-average lifetimes have increased 16–22% per year since the turn of the century.

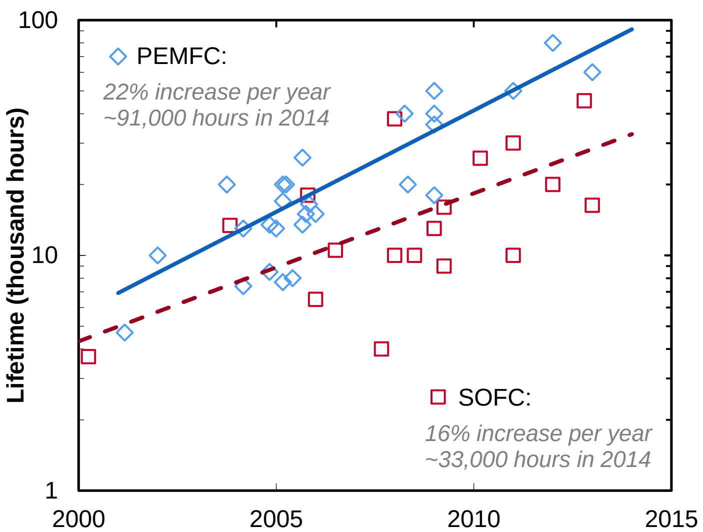

Figure 5: The improvement in fuel cell lifetimes over the past fifteen years. Data from 12 PEMFC and 9 SOFC systems [28, 42, 55, 62, 67, 72-75].

Commercial PAFCs have been operating for decades, and current systems are guaranteed for 80–130 thousand hours (12–20 years at 6,500 hours per year), with an overhaul after the first ten years [52, 76]. MCFCs on the other hand still struggle with low lifetime due to the aggressive stack chemistry and electrolyte leakage [37, 77]. Systems are expected to operate for 10 years, but mid-life stack replacement adds around 15% to the initial cost [38].

2.1.3 Reliability

Conventional heating technologies offer very high reliability with uptimes approaching 99.9%, roughly one failure every three years. As with any emerging technology, fuel cells are struggling to match this high standard.

Residential system reliability has reached 97% in the German Callux trials, with a mean time between failure (MTBF) of 1,700 hours (one failure every four months) [66]. MTBF has doubled since 2008, so the latest generation of systems is expected to continue this trend. Similarly, 90% of first-generation EneFarms suffered a fault in their first year during 2004–07, but with early teething problems overcome only 5% of systems now fail in a given year [8], which is comparable to gas boilers. In both trials, failures were broadly distributed amongst components: the stack, reformer, water circuit and electrical control system.

The maturity of large PAFCs and MCFCs translates into higher reliability, and average availability has exceeded 95% for over a decade [38, 78]. This is the upper limit seen in conventional power stations [79], and comparable to commercial CHP engines [80].

2.1.4 Degradation

All technologies suffer performance degradation over time, from gas and wind turbines to solar PV panels [81]; but this has been a particular issue for fuel cells. Until recently, cell voltage fell 0.5–2% per thousand hours, resulting in power output and electrical efficiency falling 2.5–10% per year [28]. This is partially offset by rising thermal efficiency as electrical losses emerge as resistance heating.

In recent years degradation rates have been reduced 0.5–1.5% per year in the leading PEMFCs and PAFCs [42, 82], 2% per year in MCFCs [38], and 1.0–2.5% per year in SOFCs [67, 83, 84]. End of life is often defined as power output falling 20% below initial specifications, which now occurs after 10–20 years.

2.2 The Efficiency of Competing Technologies

Energy is a fast moving sector – the goalposts for technology performance are constantly shifting, meaning cross-technology comparisons must be based on recent and robust data. Also, as seen in section 2.1, rated specifications are not necessarily representative of performance in real buildings.

Three technologies compete with fuel cells in the markets of residential and commercial heat: CHP engines, and heat pumps powered by electricity and gas. Biomass heating is a fourth option, but assessing the efficiency, practicality and sustainability of the various feedstock options would require separate in-depth assessments [48, 85, 86].

2.2.1 CHP Engines

Internal combustion engine CHP systems are less efficient than fuel cells due to losses in the conversion from heat to mechanical to electrical energy, although thermal efficiency is higher as a consequence. The Honda EcoWill is the most efficient residential-scale engine (26% electrical, 66% thermal) [87]. Electrical efficiency increases with capacity due to the use of larger bore, lower speed engines with higher compression ratios [88], moving from 25–30% LHV for residential and small commercial (1–10 kW), to 30–35% for larger commercial (20–200 kW) and 36–40% for industrial and utility scale (0.5–5 MW) [80, 88, 89]. Thermal efficiency decreases more strongly with capacity, meaning total efficiency falls from 85–92% to 73–84% over this range.

Independent laboratory testing shows that electrical efficiencies are close to manufacturer specifications, however total efficiency is around 5% lower [90]. At least three field trials have shown that performance in buildings is similar, provided that there is consistent demand to give long running hours [17, 91, 92].

External combustion, or Stirling engines have a similar overall efficiency but substantially lower electrical efficiency, around 12–18% for residential and 20–25% for larger commercial systems [89]. However, several trials demonstrated electrical efficiencies of just 6–10% as the technology is very sensitive to operating conditions and running hours [17, 93-95]. In smaller houses, negative electrical efficiency has been experienced, where less power is produced than consumed by the system's control unit [17].

2.2.2 Electric Heat Pumps

Heat pumps are characterised by their coefficient of performance (COP), which is heat output divided by electricity input to the pump under specified steady-state conditions. COP values of 3 or 4 are often quoted, and several field trials have demonstrated values in the range of 3.0–3.5 for air source heat pumps (ASHP) and 3.3–4.2 for ground source (GSHP) when operated in real houses [13]. However, performance depends strongly on the temperature of external heat collectors – either air temperature for ASHP or sub-surface temperatures for GSHP. COP falls by as much as 0.1 for every degree centigrade drop in external temperature [13].

A better measure is therefore the seasonal performance factor (SPF) which represents the annual system performance at a specific location, accounting for year-round temperatures [13]. SPF also accounts for electricity consumed by coolant pumps and auxiliary heating (as heat pumps are commonly backed up by resistance heaters for peak demand) [13, 96].

When installed and operated correctly, residential ASHP systems demonstrated annual average SPFs of 2.6–3.0 in large German field trials, while GSHPs averaged 3.3–4.0 [97, 98]. Two UK trials yielded SPF values of 2.4–2.6 for ASHP and 3.0–3.2 for GSHP [99, 100],[1] which are lower due to the colder and damper British climate, and several problems experienced with installation, system sizing and operation [101, 102]. Heat pumps are particularly sensitive to operating conditions, and a greater level of installer and user education is needed to match German standards [13].

[1] These results are derived in [48] from additional data [101, 102] to conform with the system boundary used in the German trials (SPF_{H3}).

2.2.3 Gas Heat Pumps

Two heat pump technologies use gas rather than electricity. Gas engine heat pumps use an internal combustion engine to drive the compressor, employing the CHP principle to harness waste heat from generating electricity. Gas engines can also power thermally driven absorption and adsorption reactions, using water-ammonia and zeolite chemistries in place of the vapour compression cycle [103-105].

Although small engines are less efficient than power stations, the utilisation of waste heat increases the total output by 30%, which is particularly beneficial in colder climates [105, 106]. The combination of heat recovery from the engine and the environment means 1.2–1.6 kWh of heat is produced for each kWh of primary energy consumed [107-110]. Sadly, field data are not readily available.

2.2.4 Temperature Dependence

For fuel cells amd other technologies the quantity and efficiency of heat production falls as output temperature rises. Higher temperature water/air has higher exergy content, and thus cannot be produced as efficiently. The decrease is minimal for conventional technology as the flame in combustion engines is several hundred degrees, but other technologies without combustion see a stronger drop. This is most notable with heat pumps which rely on the temperature difference between the ambient environment and heat provided to the home.

Figure 6 collates data from several experimental trials to show the profound effect that output temperature has on different technologies. The average rates of efficiency loss are:

- 1–2% per 10°C for micro-CHP engines;
- 6–9% per 10°C for fuel cell micro-CHP systems; and
- 14–19% per 10°C for heat pumps.

This highlights the importance of using low temperature heat distribution for space heating applications, and explains why high-temperature industrial processes are the most difficult to decarbonise.

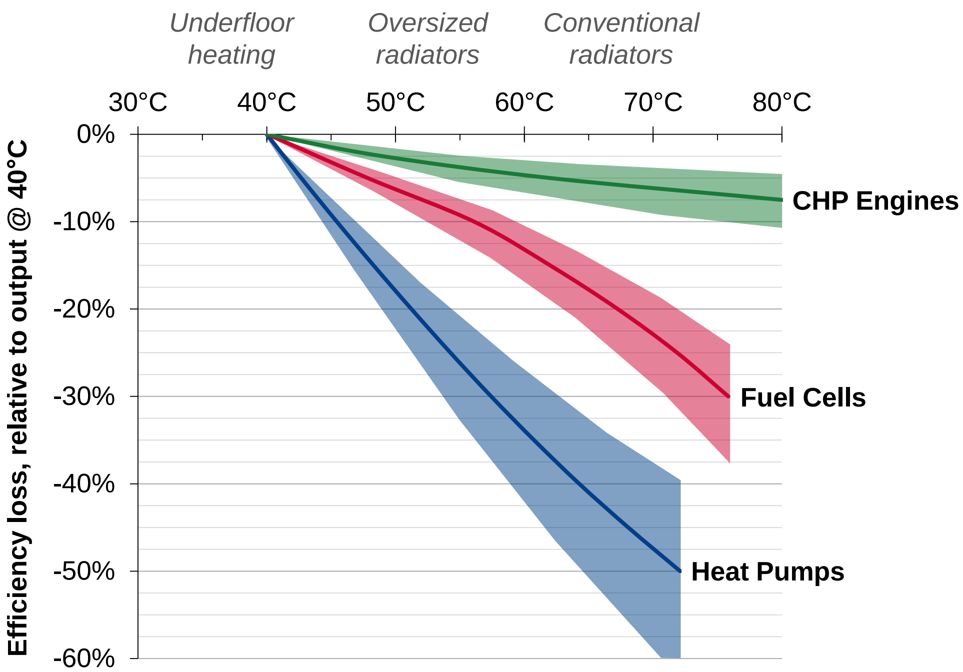

Figure 6: The impact of output temperature on the efficiency of heat production. Total system efficiency is normalised against each technology's efficiency at 40°C, with shaded areas representing the range across different models [13, 90, 111-115].

3 Methods

3.1 Comparing Efficiency across Technologies

Comparing the efficiency of fuel cells to other low-carbon technologies is non-trivial due to their diversity: heat pumps consume electricity whereas CHP technologies produce it. A common language is required, as electrical and thermal efficiency are used for CHP, yet the coefficient of performance (COP) is used for heat pumps, giving the ratio of heat out to electricity in.

MacKay argued in [3] that "no plain CHP system could ever match [the] performance" of a heat pump producing 3–4 units of heat per unit of electricity. This is fair for mid-efficiency CHP engines but not for fuel cells. These disparate technologies can be compared by plotting electrical against thermal efficiency to show their trade-off, as in [3].

The primary energy efficiency of a heat pump (from fuel input to heat output) is dependent on both the pump and the electricity used to power it. The most efficient combined-cycle gas turbines (CCGTs) operate with a gross efficiency of 60% [116]; however, parasitic self-consumption and age-related wear reduce this by 7% [81], while transmission and distribution lose another 7% in the UK [117]. Over the last five years, the British fleet of CCGTs therefore averaged 52.0% net efficiency from burner tip to plug socket [117].

3.2 Calculating the Equivalent COP for a Fuel Cell

Another method of cross-technology comparison is to adopt the measure used for heat pumps: the ratio of heat output to electricity consumed. Li *et al.* first introduced the equivalent coefficient of performance for large-scale CHP turbines [118], calculated from the electricity output sacrificed when switching from power-only to cogeneration mode via the introduction of a virtual bottoming cycle [119]. Lowe then outlined a similar method of treating CHP plants as having a virtual steam cycle equivalent to a heat pump, meaning the 'Z factor' of the CHP plant can be treated as its COP [120]; a point reiterated by MacKay in the UK government's Heat Strategy [121].

These methods are valid for considering large thermal machines such as a 100 MW cogeneration plant, but they cannot be translated to electrochemical systems which have no meaningful 'power-only' mode. The advance made here is to adapt this concept to fuel cells by considering a plausible counterfactual – the process of 'system expansion' used in in life cycle assessment (LCA) methodology. By expanding the 'system' to the entire power sector, the equivalent COP[2] of a fuel cell can be calculated as its heat output divided by the power output that is 'sacrificed' by consuming gas in the fuel cell instead of a (presumably more efficient) CCGT power station (the best alternative technology).

The equivalent COP is calculated from the thermal efficiency of the fuel cell (η_{heat}) divided by the difference between the electrical efficiency of the fuel cell (η_{elec}) and a CCGT (η_{CCGT}) – the additional electricity that could have been produced if gas was used in a power station instead of the fuel cell:

$$EqCOP = \frac{\eta_{heat}}{\eta_{CCGT} - \eta_{elec}} \qquad (1)$$

3.3 Calculating the Carbon Intensity of Heat and Power

By utilising both electricity and heat on-site, fuel cell CHP achieves significant savings in CO_2 emissions relative to centrally generated electricity and a conventional heating. Several methods exist for placing a value on the carbon content of electricity from CHP systems, as the total emissions from the system must be allocated between the electrical and heat outputs [88, 122]. A typical fuel cell emits 500–600 gCO_2 in producing 1 kWh of electricity and 1.5 kWh of heat; these emissions can be attributed to each product equally, weighted by their exergetic or economic value, or by estimating the 'net emissions' required to produce just one output [123].

For example, if the 1.5 kWh of heat had not been produced by the fuel cell, it would have been produced by some other means: a 'reference technology'. A common method of allocation is therefore to estimate how much fuel the reference technology would have consumed in delivering that heat, and then subtract this from the fuel cell's consumption to give the net amount of fuel used solely to produce electricity.

[2] Equivalent SPF (seasonal performance factor) is perhaps a more accurate description as it gives the year-round performance during all weather conditions

In a similar manner, the carbon intensity of electricity can be calculated by crediting heat produced by CHP with avoided production from a condensing boiler. The carbon intensity of fuel cell electricity (C_{FC}^{elec}) is the total carbon emitted from producing one kWh of electricity minus the emissions that are avoided because of the co-produced heat. Total emissions equal the carbon intensity of the gas burnt (C_{fuel}) divided by the electrical efficiency of the fuel cell (η_{elec}). Avoided emissions equal the carbon intensity of displaced heat (C_{boiler}) multiplied by the quantity of heat produced with each kWh of electricity, which is the ratio of the fuel cell's thermal efficiency (η_{heat}) to its electrical efficiency.

$$C_{FC}^{elec} = \frac{C_{fuel}}{\eta_{elec}} - \left(C_{boiler} \cdot \frac{\eta_{heat}}{\eta_{elec}} \right) \tag{2}$$

The method of equation 2 is relatively standard, being used in the US EPA's measure of 'effective electrical efficiency' [88] and to promote commercial CHP systems [50, 51]. A less widely considered metric is the carbon intensity of heat, as opposed to electricity. The only apparent use of this metric is in the UK government's Standard Assessment Procedure (SAP) for the calculation of CO_2 emissions from community heating (worksheet 12b in [124]), and as one possible option for calculating the emission factor for purchased heat or steam [122]. It has not been applied to individual CHP plants or microgeneration, and has received little if any attention in academic literature. Equation 3 gives the calculation of the carbon intensity of heat:

$$C_{FC}^{heat} = \frac{C_{fuel}}{\eta_{heat}} - \left(C_{grid} \cdot \frac{\eta_{elec}}{\eta_{heat}} \right) \tag{3}$$

The carbon intensity of fuel cell heat (C_{FC}^{heat}) equals the total emissions from producing one kWh of heat minus the emissions that are avoided because of the co-produced electricity. Total emissions equal the carbon intensity of gas divided by the fuel cell's thermal efficiency, and avoided emissions equal the carbon intensity of grid electricity (C_{grid}) multiplied by the quantity of electricity that is produced with one kWh of heat.

For fairness, it is assumed that the best available standard technology is displaced, usually a condensing gas boiler. The carbon intensity of natural gas is 205 g/kWh (LHV), and modern condensing boilers average 94 ± 4% efficiency in real world usage, producing heat with 218 g/kWh of CO_2 [61, 125].

3.4 The Importance of Average and Marginal Electricity

The carbon intensity of grid electricity is open to interpretation, as it varies between countries, seasons and with time of day. In Britain, central generation has an average carbon intensity of 500–520 g/kWh [117]. However, this average intensity varies over time as the mix of online stations changes in response to demand. Emissions intensity is lower overnight, as nuclear stations run at an almost constant level, meaning that fossil stations turn down or off.

It is therefore marginal and not average emissions which matter when calculating the impact of distributed generation. A change in demand, caused by heat pumps consuming or fuel cells producing electricity, will not force the same reaction from all power stations on the system. Some stations are inflexible (nuclear) or uncontrollable (wind), leaving gas, coal and hydro stations to respond to changes in demand. The specific station (or mix of stations) which responds is known as the *marginal* station, and it is the marginal emissions intensity which determines the actual CO_2 reduction from demand-side technologies. While average emissions intensity is around 510 g/kWh in the UK, marginal emissions intensity averaged 690 g/kWh from 2002–09 [126], and 640 g/kWh from 2009–12 [127]; approximately the mid-point between gas CCGT (410 g/kWh) and coal (950 g/kWh) [48].

Quantifying marginal emissions is a controversial topic, and so average emissions are used for the central results in this study, with a range of marginal stations (from CCGT to coal) considered in the supplementary results.

4 Results

4.1 Fuel Cell vs. Heat Pump Efficiency

Figure 7 plots efficiency data from the previous section for traditional and low-carbon systems, based on demonstrable real-world performance as opposed to rated manufacturer specifications.

Traditional systems are first plotted:

1) Electricity from the average generation mix (based on the UK with 38.6% efficiency [117]), and heat from condensing boilers (94% efficient [61]);
2) The dashed line connecting these is the traditional frontier, which technologies must beat to offer any improvement in efficiency.

Then the 'best' low carbon systems are considered:

3) Electricity from the most efficient type of power station (CCGTs at 52.0%) [117], and heat from ground source heat pumps installed to the highest standards (COP 3.3–4.0) [97, 98];
4) The vertical intercept for electricity-consuming technologies is multiplied by the CCGT efficiency, as a COP 4 heat pump will produce 2.08 units of heat from one unit of natural gas burnt in a CCGT;
5) The green line connecting these points is the all-electric frontier, which is the best available efficiency from the established low-carbon solution; the shaded area covers the range of potential GSHP efficiency seen in practice.

Finally, the efficiency of gas-fired CHP is added:

6) CHP engines from 1 kW to 5 MW [80, 88, 89], with total efficiency reduced by 5% to account for demonstrated real-world losses [17, 90];
7) Fuel cells, based on the real-world field performance reported in Table 2.

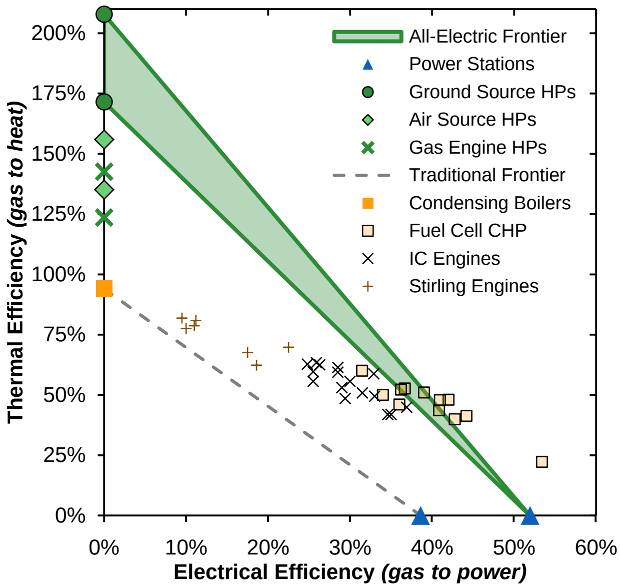

Figure 7: Comparison of the electrical and thermal efficiency of residential heating technologies, showing that fuel cells equal or outperform the best alternative low-carbon technologies. See also supplementary results.

As should be expected, all forms of low-carbon heating exceed the performance of condensing gas boilers. Engine-based CHP and gas heat pumps fall short of the low-carbon frontier as MacKay argued, having a similar efficiency trade-off to air-source heat pumps at present. However, fuel cells lie around or above the frontier, implying that the best fuel cells (predominantly SOFC and MCFC) are more efficient than the best available heat pumps *even if* those heat pumps are only powered by the most efficient power stations.

In practice, it cannot be guaranteed that heat pumps will be solely powered by CCGTs as a mix of gas and lower efficiency coal typically comprise the marginal power stations which respond to changes in demand [126]. A less optimistic assumption would shift the all-electric frontier in Figure 7 to the left (as generation efficiency decreases) and also downwards (as heat pumps receive less electricity for conversion into heat). Other situations are explored in the supplemental results section, showing that below a power station efficiency of 46%, all the fuel cells in Figure 7 outperform the best SPF 4 heat pumps.

4.2 The Equivalent COP of Fuel Cells

Continuing the assumption that central power comes solely from a 52% efficient CCGTs, the equivalent COP of PEMFCs ranges from 2.8–3.4; PAFC and MCFC are slightly higher at around 4.1 and 4.8; and the best Japanese SOFCs attain 5.3. The CFCL BlueGen is equivalent to a heat pump with an *infinite* COP, as its electrical efficiency is higher than a CCGT and it delivers useful heat. For comparison, the CHP engines plotted in Figure 7 have equivalent COPs of 2.2–2.8; lower than both air- and ground-source heat pumps, as previously thought [3].

Equivalent COP depends on the efficiency of both the fuel cell and the power station that could have instead been used. Figure 8 plots this sensitivity for different fuel cell technologies. If fuel cells displace power from an equal share of CCGTs (52%) and standard coal boilers (40%), equivalent COPs are substantially higher: 4.3–5.5 for PEMFC; 8.4–12.0 for PAFC and MCFC; and 14.4–∞ for SOFC.

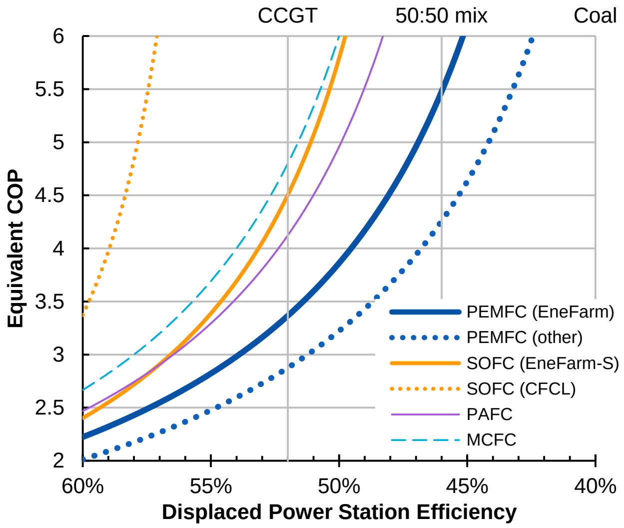

Figure 8: Sensitivity of fuel cell's equivalent COP to the assumed electrical efficiency of power stations which would otherwise be used.

Equivalent COP is very sensitive to fuel cell performance, as the two terms of equation 1's denominator ($\eta_{CCGT} - \eta_{elec}$) are close in magnitude. Table 3 shows how the equivalent COP rises when the rated efficiency is used in place of real-world performance, calculated against 52% efficient CCGT. For example, the 5% penalty experienced by the Aisin Seiki EneFarm-S [67, 69] reduces its equivalent COP from 8.0 down to 5.3.

Table 3: The equivalent COP for selected fuel cell models when displacing power from 52% efficient CCGTs, showing the impact of the gap between 'real-world' performance and laboratory specifications for fuel cells.

	Field Performance	Rated Specifications
Panasonic & Toshiba (EneFarm)	3.31–3.44	4.13–4.32
GS, FCPower & Samsung	2.79–2.88	
Vaillant, Baxi & Hexis (Callux)	2.78–3.08	3.19–3.53
Aisin Seiki & JX (EneFarm-S)	3.94–5.32	5.14–7.98
CFCL	∞	∞
Purecell	3.94	4.82
Fuji	4.34	4.92
FuelCell Energy	4.82	8.69

4.3 Potential for Carbon Mitigation

It is difficult to make generalisations about the absolute CO_2 saving achieved by fuel cells as this varies between countries, predominantly due to the carbon intensity of grid electricity [128]. In Japan and Germany, manufacturers advertise 0.7–1 kW systems as saving 1.3–1.9 TCO_2 per year in four-person households (reductions of 35–50%) [8, 43, 55, 129], while the 1.5 kW CFCL BlueGen saves around 3 tonnes per year in Australia [7]. Commercial-scale systems (350–400 kW) offer savings of 700–1,300 TCO_2 per year in Germany and the US [38, 78]. The general consensus is that in countries with a typical fossil-rich electricity system, fuel cells (regardless of technology) can save 1.5–2 tonnes of CO_2 per year, per kW of installed capacity.

As with other low carbon technologies (e.g. solar PV and nuclear), these savings must be balanced against the carbon emissions from construction. Fuel cells are larger and heavier than the gas boilers they replace, and require nickel and platinum catalysts which are extremely energy intensive to produce.

Several life cycle assessments (LCAs) have estimated these carbon emissions – known as the embodied carbon or the carbon footprint – by considering how the fuel cell is manufactured, the energy and materials required, and how these materials are produced. Manufacturing a 1 kW residential CHP system emits 0.5–1 TCO_2, while a 400 kW commercial system results in 100–400 tonnes emitted [128, 130-133]. While there are differences between stack technologies, these are outweighed by differences in the country of manufacture and production methods employed by different brands.

If these emissions are averaged over the system's lifetime they equate to 10–20 grams of CO_2 per kWh (g/kWh) of electricity, or 8–16 g/kWh of heat [128]. For comparison, the carbon intensity of construction is widely estimated to be 40–80 g/kWh for solar PV and 10–30 g/kWh for nuclear [134, 135] – suggesting that fuel cells are a relatively low-impact technology.

4.4 Carbon Intensity of Fuel Cell Electricity

To avoid the ambiguity caused by different national electricity mixes, the carbon intensity (in g/kWh) can be calculated instead of the absolute emissions reduction. This then depends only on the performance of the fuel cell and the heating system that is displaced.

When displacing heat from a condensing gas boiler, the carbon intensity of electricity from fuel cells lies in the range of 240–280 g/kWh – about two-thirds that of CCGTs, and a quarter that of coal power stations. Electricity from fuel cells is therefore substantially lower than either the average or marginal emissions from most national electricity systems. The above values are based on real-world operating efficiency; if rated specifications are used (without the penalties shown in Table 2) the carbon intensity falls to 215–265 g/kWh.

Taking the Panasonic EneFarm operating in a Japanese house as an example, η_{elec} = 36.7% and η_{heat} = 52.6%. For each kWh of electricity produced, 2.73 kWh of fuel is consumed and 559 gCO_2 is produced. The fuel cell also produces 1.43 kWh of heat, which would otherwise have needed 1.52 kWh of gas to be burnt in a condensing boiler, thus saving 313 g of emissions. The net carbon intensity of electricity is therefore 246 g/kWh, which is similar to that advertised for PAFC (225 g/kWh) and MCFC systems (238–308 g/kWh) [50, 51].

Figure 9a plots carbon intensity as a function of their electrical and thermal efficiency, showing fuel cells alongside IC engines (which average 255–315 g/kWh) and Stirling Engines (240–340 g/kWh). There is significant overlap between the carbon intensity of electricity from each technology as electrical and thermal efficiency are traded off almost 1:1.

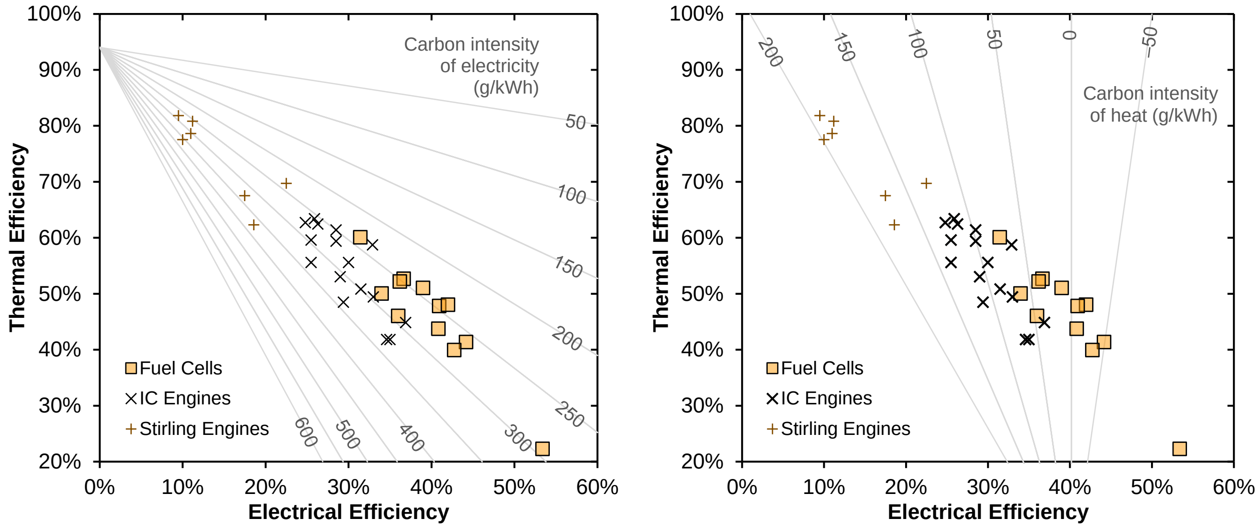

Figure 9: The carbon intensity of (a) electricity and (b) heat from fuel cells and other CHP technologies, when displacing (a) heat from a condensing boiler and (b) electricity from the average UK grid mix. See also supplementary results.

4.5 Carbon Intensity of Fuel Cell Heat

If a fuel cell's electrical output is credited with avoided central generation, the carbon intensity of heat is around zero in the UK. Using the above example of a PEMFC: 1.43 kWh of heat results in the production of 559 g of CO_2; the 1 kWh of coproduced electricity reduces national emissions by around 510 g/kWh (assuming average grid mix); and so the heat has a net carbon intensity of 34 g/kWh $\left(\frac{559-510}{1.43}\right)$, a six-fold improvement over modern condensing boilers. Repeating the calculation with the more efficient Aisin Seiki SOFC (η_{elec} = 44.2% and η_{heat} = 41.3%) results in heat output being carbon negative, with an intensity of –49 g/kWh.

It may seem counter-intuitive that a gas-fired technology can produce zero carbon heat; however, this is possible when electricity is produced with lower emissions than the grid *and* heat is utilised rather than wasted. Any gas-fired technology with an electrical efficiency over 40% will have lower emissions than the UK grid average; SOFCs and MCFCs fall into this category, with PAFCs and the better PEMFCs not far away. Figure 9b plots the carbon intensity of heat from CHP: fuel cells average –110 to 85 g/kWh; IC engines 70–120 g/kWh; and Stirling engines 155–200 g/kWh. For comparison, heat from GSHPs powered solely by CCGTs averages 100–120 g/kWh, rising to 130–150 g/kWh for ASHPs. If powered by the average UK grid mix, these heat pump numbers are 30% higher.

The contour lines in Figure 9b shift to the right as the carbon intensity of grid electricity decreases, reducing the attractiveness of gas-fired CHP. If grid carbon halved to 255 g/kWh, then central electricity would become equivalent to that from the CHP technologies calculated in section 4.4. The carbon intensity of heat from all CHP technologies would then converge to that of burning gas in a condensing boiler, and thus CHP no longer offers a carbon benefit. Alternative scenarios are explored in the supplemental results.

The UK's average grid intensity is expected to fall to this level in the early 2020s by the latest Carbon Budget [136]; however, it should be noted that marginal grid intensity cannot be expected to fall below 400 g/kWh (that of modern CCGTs) until a flexible and controllable low carbon technology has been found.

5 Conclusions

Globally, demand for heat makes up nearly half of overall energy consumption and CO_2 emissions, but decarbonising heat has received relatively little attention compared to electricity and transport [4]. As many countries use high-efficiency natural gas for heating there is not yet a cost-effective, low-carbon alternative. Fuel cells have not featured widely in European decarbonisation strategies, losing out to proposals for electrification with heat pumps [136, 137].

This paper provides the evidence and methods needed to compare fuel cells to traditional heat and power systems and to competing low carbon technologies. A common language is developed for comparing fuel cells (and other CHP technologies) directly with heat pumps, first by calculating the equivalent coefficient of performance (COP). The carbon intensity of electricity is calculated by the method of displacement, and a logical extension is proposed to calculate the carbon intensity of heat for comparison with heat pumps.

The current state of the art of fuel cells for residential and commercial CHP is analysed, revealing some key points:

- Electrical and thermal efficiency are high, but fall when the system is operated away from its rated output or repeatedly cycled on and off;
- The efficiency demonstrated in houses is up to a tenth lower than rated specifications, which mirrors experience with heat pumps and CHP engines;
- Lifetime and reliability are improving rapidly towards the standards of competing microgeneration technologies.

Even with the optimistic assumption that all central electricity is produced from high-efficiency CCGT stations, the equivalent COP of fuel cells ranges from 2.8–5.3, and for the best-performing SOFC system it is infinite, as the SOFC requires less gas to produce electricity than a CCGT would, and provides 'free' heat as an aside. When considering the average power mix for the UK (which has a typical mix for a high-income country), the equivalent COPs rise to between 4 and 14 – significantly higher than could ever be achieved with electric or gas heat pumps.

The carbon intensity of fuel cells can be summarised as either:

- Heat equivalent to a condensing boiler and electricity with half the carbon intensity of the UK average grid mix (two-thirds that of the best CCGT power stations); or
- Electricity equivalent to the average UK grid mix, and heat that is zero or even negative carbon.

By developing common metrics for comparing the different technologies and respecting how they work within the interconnected electricity system it is shown that fuel cells deliver heat with a higher efficiency that can be obtained by the best heat pumps, and that this heat output leads to no change – or even a net decrease – in national CO_2 emissions due to the displacement of higher-carbon grid electricity. Efforts to decarbonise the electricity system with renewables and nuclear power will not significant impact on these conclusions, as they cannot respond easily to changes in demand, and unlikely to ever become 'marginal' generators.

The best fuel cells should arguably be treated as a zero-carbon heating technology. Just as heat pumps can be classified as a renewable technology despite consuming grid electricity; the same logic dictates that the most efficient fuel cells should perhaps also be classified as renewable, despite consuming natural gas. At present, fuel cells are excluded from such consideration; for example the definition of renewable heat in the EU's Renewable Energy Directive includes electric heat pumps powered by fossil-rich grid electricity, but excludes CHP systems which can offer similar or better efficiency and carbon emissions [138].

There is a strong opportunity for fuel cells to contribute to low-carbon heating the world over by combining high efficiency, large annual energy output and broad applicability to the buildings sector. Fuel cells could play a core role in national decarbonisation strategies, and policy approaches should level the playing field for this promising technology [4].

6 Acknowledgements

This work was funded by the Hydrogen and Fuel Cell SUPERGEN Hub (EP/J016454/1) through the RCUK Energy Programme. The author thanks the team who wrote the H2FC White Paper which provided the inspiration for this work: Paul Ekins, Paul Dodds, Adam Hawkes, Will McDowall, Francis Li, Philipp Grünewald, Tia Kansara and Paolo Agnolucci. Thanks are given also to Jennifer Gangi, Klaus Ullrich, Jonathan Carter and David Hart for providing invaluable information, and to Robert Staffell for comments and suggestions on the text.

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Supplementary Data for Zero Carbon Infinite COP Heat from Fuel Cell CHP

This addendum provides supplementary data and results to the paper "Zero Carbon Infinite COP Heat from Fuel Cell CHP" published in Applied Energy. Please cite this report in the same manner as the main paper:

Staffell I, 2015. *Zero carbon infinite COP heat from fuel cell CHP*. Applied Energy, **147**: 373–385.

Data – Fuel Cell Efficiencies

Table S1 presents the dataset used for fuel cell efficiency, which lies behind the figures in the main paper and in the results presented in this supplement:

- 'Rated Efficiency' is that specified by the manufacturer, usually recorded according to a national standard testing procedure, e.g. EN 50465 in Europe;
- 'Real-World Gap' gives the drop in performance when systems are operated in real homes and businesses, caused by the effects outlined in section 2.1 of the main paper;
- 'Field Efficiency' gives the values that were used to produce results – so that they represent the best estimate of performance of fuel cells in real world usage.

Table S1: Efficiency dataset for fuel cell CHP systems [1-12].

	Technology	System	Rated Efficiency		Real-World Gap	Field Efficiency	
			Electrical	Thermal		Electrical (η_{elec})	Thermal (η_{heat})
A	PEMFC	Panasonic EneFarm	39.0%	56.0%	6%	36.7%	52.6%
B	PEMFC	Toshiba EneFarm	38.5%	56.0%	6%	36.2%	52.2%
C	PEMFC	GS EcoGener	36.0%	46.0%	0%	36.0%	46.0%
D	PEMFC	Samsung RPG	34.0%	50.0%	0%	34.0%	50.0%
E	PEMFC / SOFC	Callux *(average of Vaillant, Baxi & Hexis)*	33.0%	63.0%	5%	31.4%	60.0%
F	SOFC	Aisin Seiki EneFarm-S	46.5%	43.5%	5%	44.2%	41.3%
G	SOFC	Rinnai EneFarm-S	45.0%	42.0%	5%	42.8%	39.9%
H	SOFC	JX EneFarm-S	43.0%	46.0%	5%	40.9%	43.7%
I	SOFC	CFCL BlueGen	60.0%	25.0%	11%	53.4%	22.3%
J	PAFC	Fuji FP-100i	42.0%	49.0%	3%	41.0%	47.8%
K	PAFC	ClearEdge PureCell	42.0%	48.0%	3%*	39.0%	51.0%
L	MCFC	FuelCell Energy DFC	47.0%	43.0%	5%*	42.0%	48.0%

For systems A–J the real-world gap is taken to be a relative decrease in both electrical and thermal efficiency (i.e. for System A: 39.0% × (1 – 6%) = 36.7%). The performance of systems K and L (indicated by *) are better described by a linear decline in electrical and increase in thermal efficiency, and so these systems are modelled differently.

Where field trial results are available for the latest version of a fuel cell, the real world gap is taken from Table 2 in the main paper. Recent field trials are not available for most systems (as they have moved to unmonitored commercial sales). The real world gap is therefore estimated with the assumption that system control has improved over time, and thus the gap for current systems is smaller than that experienced during demonstration phases. This is seen for Generations I and II of the Callux systems, where the gap decreased from 16% to 8.5%, and thus a smaller gap is envisioned for the current Generation III systems.

Results – Equivalent COP of Fuel Cells

Figure S1 replicates Figure 7 from the main paper in greater detail, with the fuel cell models identified A–L, corresponding to the labels given in Table S1. It can be seen that PEMFC systems (A–E) lie within or below the performance of ground source heat pumps, whereas the other technologies (F–L) lie at the upper end or above this.

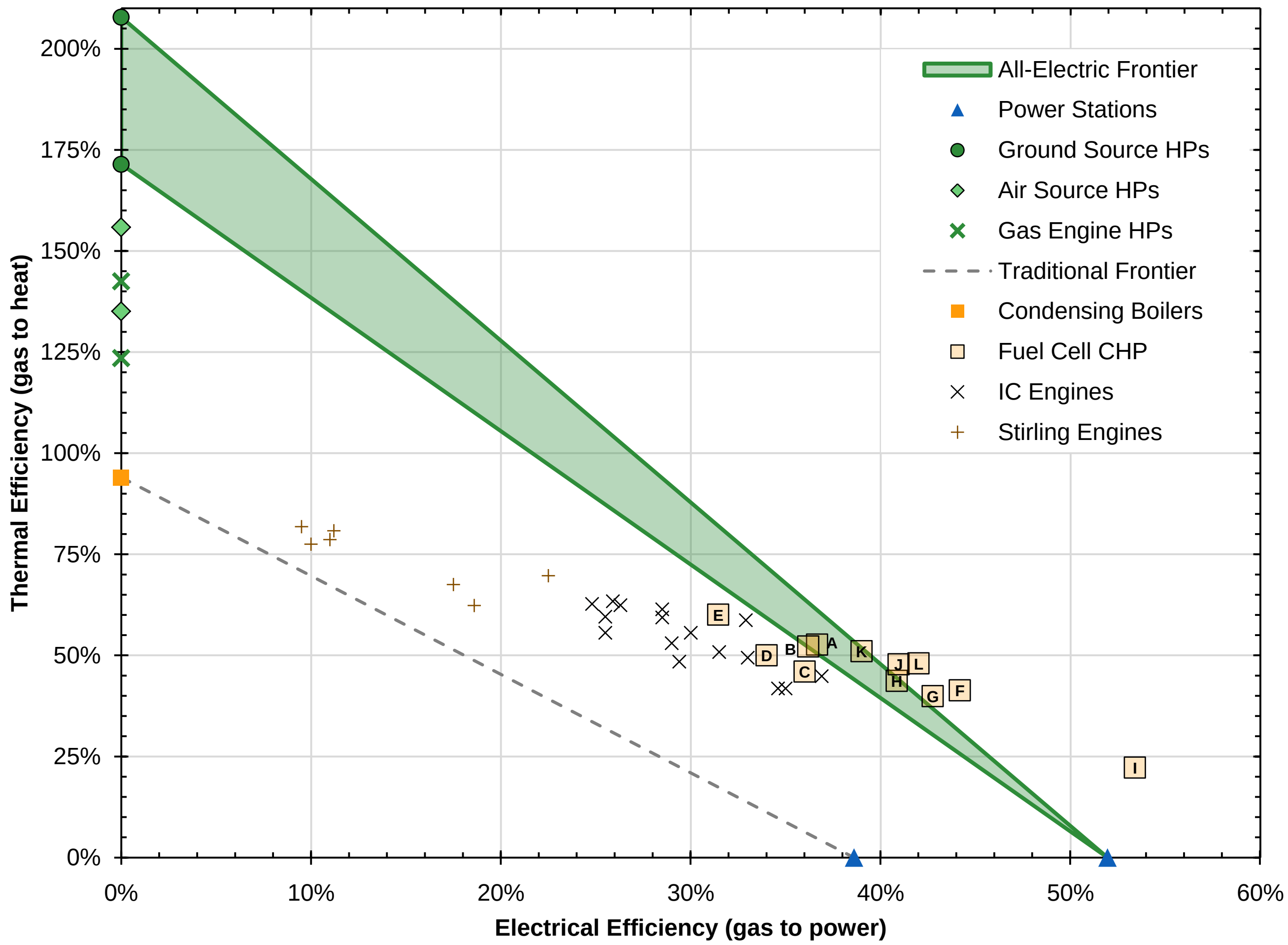
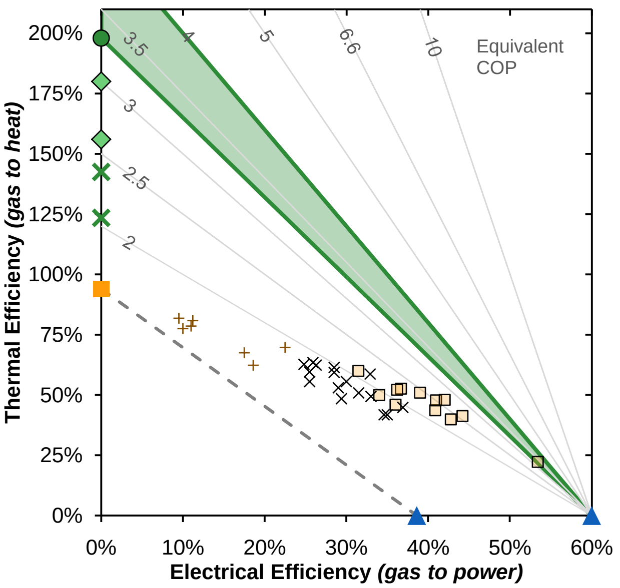


Figure S1: Comparison of the electrical and thermal efficiency of residential heating technologies.

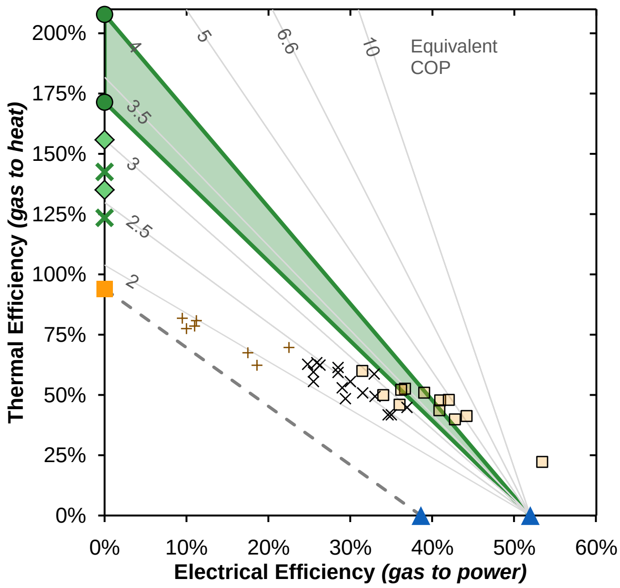
Different assumptions about the electricity source will shift the all-electric frontier in both horizontally (as generation efficiency changes) and also vertically (as heat pumps receive more or less electricity for conversion into heat).

This is demonstrated in Figure S2, which re-plots Figure 7 from the main paper using a range of assumptions for central electricity generation efficiency (η_{grid}):

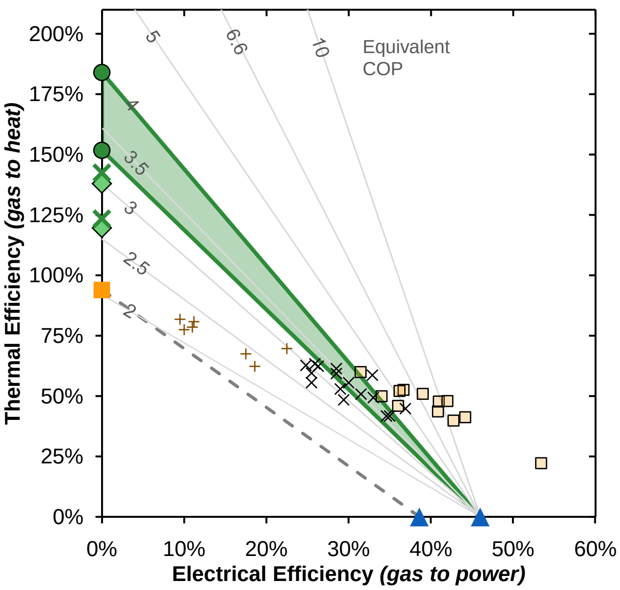
- 60% is the maximum gross efficiency of a modern CCGT when new [13], excluding parasitic consumption by ancillary equipment in the power station, and losses in transmission and distribution;
- 52% is the average efficiency of CCGTs in the UK [14], and equivalent to the above 60% CCGT with 2% parasitic losses, 7% transmission losses, and 5% loss due to age-related wear (~10 years old);
- 46% is a plausible estimate for the marginal efficiency of power stations in the UK, based on an equal mix of CCGT (52%) and coal (40%) – based on the observation that marginal emissions intensity lies half way between that of CCGT and coal plants [15];
- 40% is the maximum efficiency of new coal-fired power stations [16, 17], although it should be noted that none are likely to be built in the UK due to environmental regulations. For reference, the average efficiency of coal plants in the UK is 36% [14].



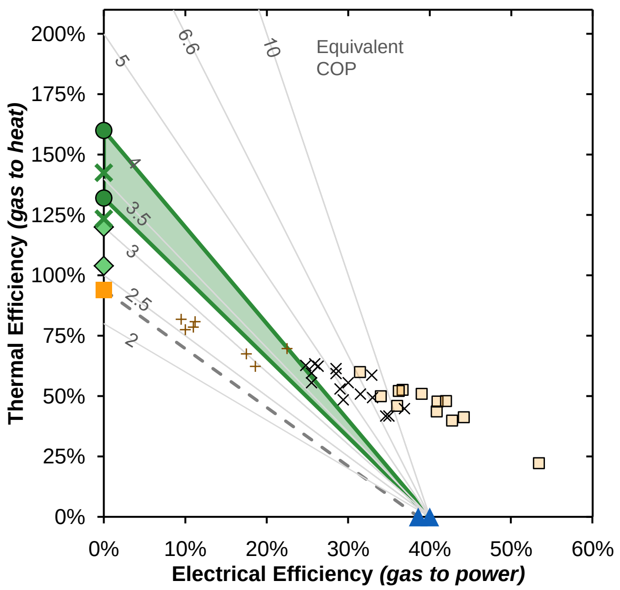
Best possible CCGT (η_{grid} = 60%)



Average UK CCGT (η_{grid} = 52%)



Equal mix of gas and coal (η_{grid} = 46%)



Best possible coal (η_{grid} = 40%)

Figure S2: Variation in equivalent COP for CHP systems for different assumed efficiencies for grid electricity.

Figure S2 includes contours showing equivalent COPs ranging from 2 up to 10, to assist in visualising how CHP technologies compare to heat pumps under the different assumptions.

Table S2 lists the equivalent COP for each fuel cell system calculated for the four values of η_{grid}. If heat pumps could be powered solely by CCGTs (as is sympathetically assumed in the main paper) then fuel cells are generally on a par with ground source heat pumps. However, if it is assumed that heat pumps are powered by a mix of coal and gas (which is perhaps the best assumption that can be made without performing a detailed study along the lines of Hawkes' [15]) then fuel cells show a clear advantage over heat pumps. PEMFCs have an equivalent COP of 4.8 ± 0.7, and other technologies have 12.0 ± 5.6 (not including the CFCL Bluegen which is ∞). Furthermore, if it is assumed that electricity is generated with an efficiency of 40% (which is coincidentally the efficiency of new coal plants, and the average efficiency of the UK grid),[14] then all SOFCs offer operate with the equivalent of infinite COP, as does one model of PAFC and MCFC.

Table S2: Equivalent COP values for each fuel cell system under the four scenarios presented in Figure S2.

			Assumed efficiency for grid electricity (η_{grid})			
	Technology	**System**	**60%**	**52%**	**46%**	**40%**
A	PEMFC	EneFarm (Panasonic)	2.26	3.43	5.64	15.76
B	PEMFC	EneFarm (Toshiba)	2.19	3.30	5.32	13.69
C	PEMFC	GS EcoGener	1.92	2.88	4.60	11.50
D	PEMFC	Samsung RPG	1.92	2.78	4.17	8.33
E	PEMFC / SOFC	Callux (Vaillant, Baxi, Hexis)	2.10	2.92	4.13	7.02
F	SOFC	EneFarm-S (Aisin Seiki)	2.61	5.28	22.64	∞
G	SOFC	EneFarm-S (Rinnai)	2.31	4.31	12.28	∞
H	SOFC	EneFarm-S (JX)	2.28	3.92	8.49	∞
I	SOFC	CFCL BlueGen	3.37	∞	∞	∞
J	PAFC	Fuji FP-100i	2.51	4.32	9.46	∞
K	PAFC	ClearEdge PureCell	2.43	3.92	7.29	51.00
L	MCFC	FuelCell Energy DFC	2.67	4.80	12.00	∞

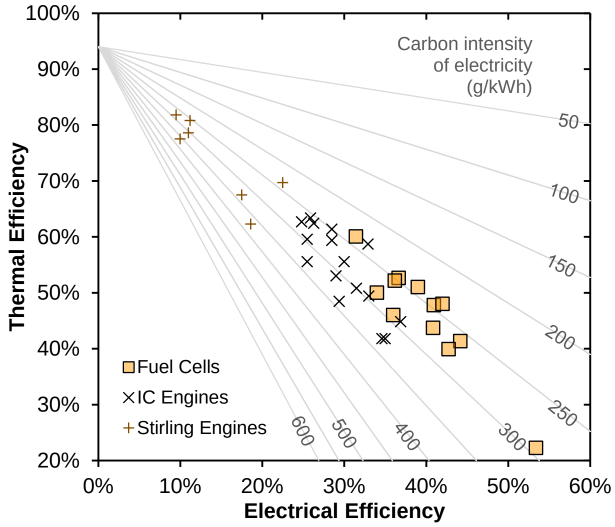
Results – Carbon Intensity of Fuel Cell Electricity

The carbon intensity of electricity from fuel cells depends on the assumption made for the displaced heating technology. In the main paper this was a condensing gas boiler, which is fairly uncontentious.

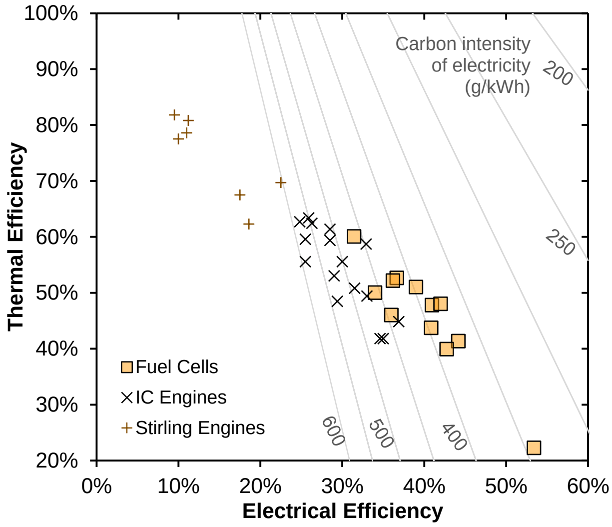
An alternative scenario could be that householders and businesses face the choice between installing a fuel cell or a top-performing ground source heat pump (SPF = 4.0). Figure S3 and Table S3 present the carbon intensity of electricity from fuel cells, with the reference technology being a gas boiler (as in Figure 9 of the main paper), and heat pumps powered by gas, coal, and an equal mix of the two.

Taking the example of heat pumps powered exclusively by CCGTs (η_{grid} = 52%): this raises the primary energy utilisation of the reference technology from 94% (condensing boiler efficiency) to 208% (the efficiency with which natural gas is used to move ambient subterranean heat into the home), and reduces the carbon intensity of heat (CI_{heat}) from 218 g/kWh (gas boiler) to just 99 g/kWh (205 / 52% / 4.0).

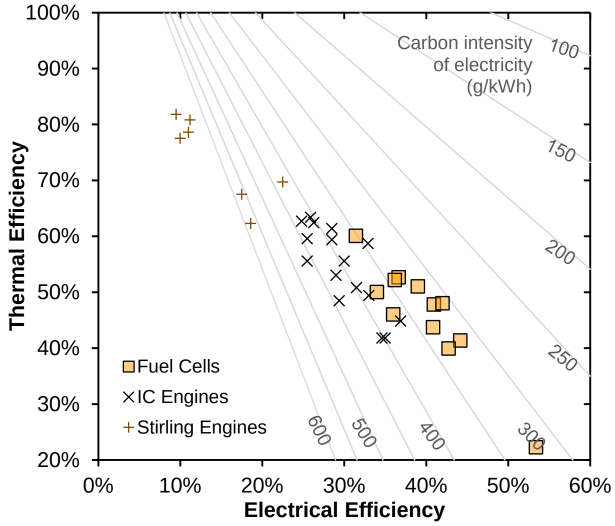
In this best-case scenario, electricity from fuel cells has a carbon intensity of 405 ± 37 g/kWh, which is broadly the same as the carbon intensity of electricity from a CCGT (395 g/kWh). In all other cases, fuel cells offer lower carbon electricity than a CCGT.



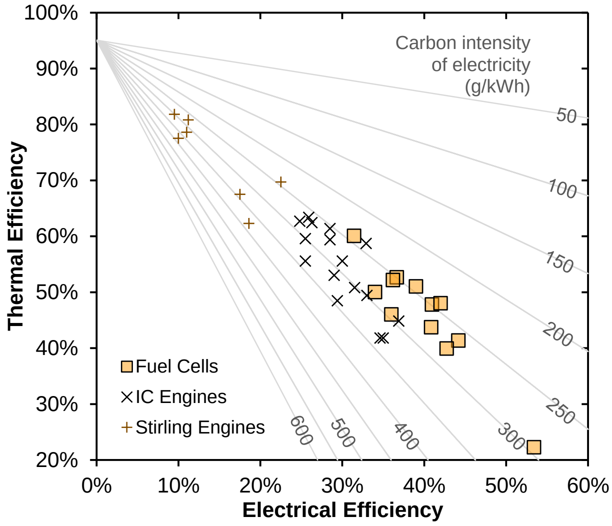
Condensing gas boiler (CI_{heat} = 218 g/kWh)



Heat pumps using average CCGT (CI_{heat} = 99 g/kWh)



Heat pumps using gas and coal (CI_{heat} = 157 g/kWh)



Heat pumps using best coal (CI_{heat} = 215 g/kWh)

Figure S3: The carbon intensity of electricity from fuel cells when displacing heat from different sources.

Table S3: Carbon intensity of electricity from fuel cells for different displaced heating scenarios.

			Carbon intensity of displaced heat (CI_{heat})			
	Technology	**System**	**218**	**99**	**157**	**215**
A	PEMFC	EneFarm (Panasonic)	243	418	334	250
B	PEMFC	EneFarm (Toshiba)	249	424	340	256
C	PEMFC	GS EcoGener	288	444	369	294
D	PEMFC	Samsung RPG	279	458	372	286
E	PEMFC / SOFC	Callux (Vaillant, Baxi, Hexis)	231	464	352	240
F	SOFC	EneFarm-S (Aisin Seiki)	258	372	317	262
G	SOFC	EneFarm-S (Rinnai)	274	388	333	278
H	SOFC	EneFarm-S (JX)	266	396	334	271
I	SOFC	CFCL BlueGen	292	343	318	294
J	PAFC	Fuji FP-100i	243	386	317	249
K	PAFC	ClearEdge PureCell	237	397	320	244
L	MCFC	FuelCell Energy DFC	236	375	309	242

Results – Carbon Intensity of Fuel Cell Heat

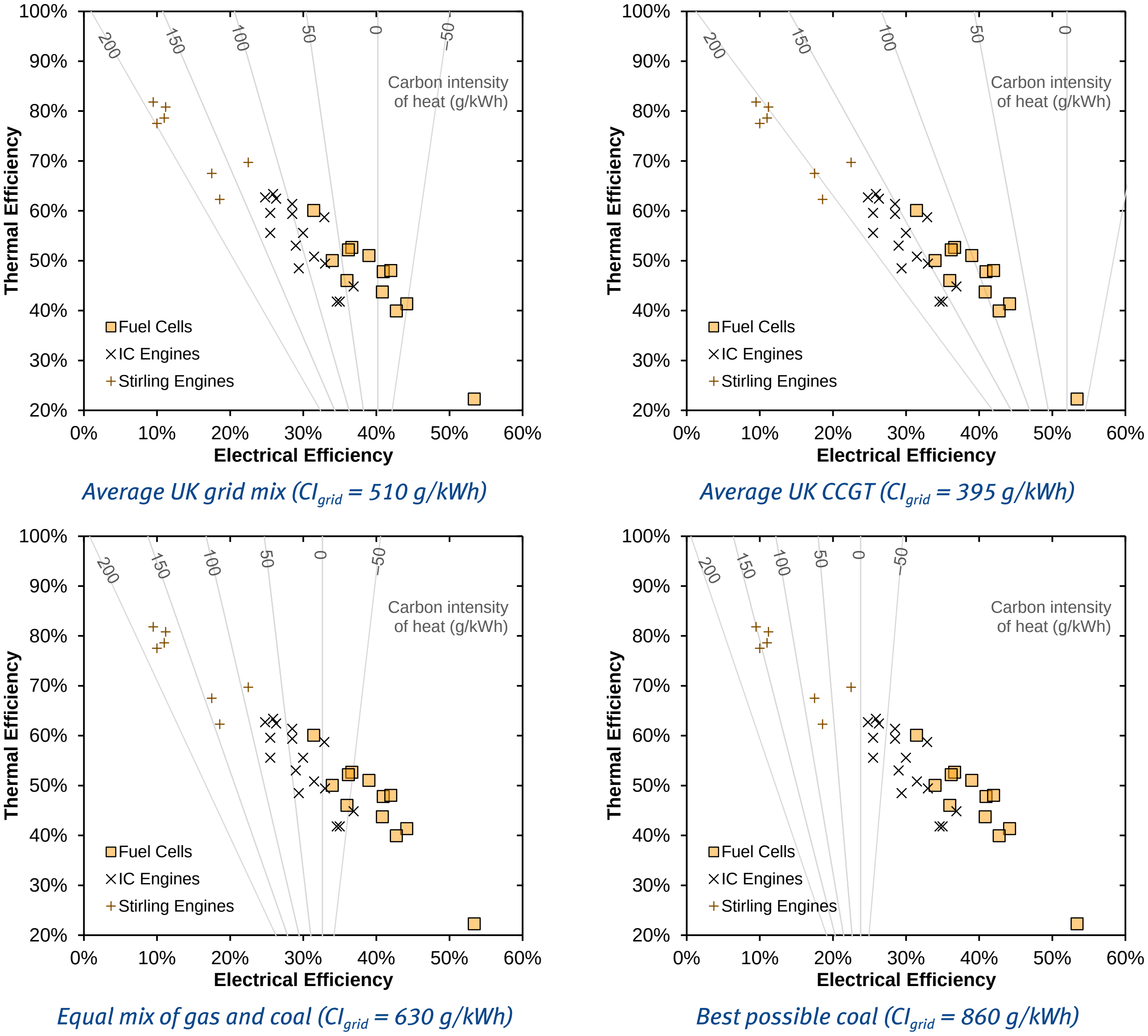
Conversely to the previous section, the carbon intensity of heat from fuel cells depends on the assumption made for the displaced electricity generator. The main paper considered the average grid mix in the UK, this section considers electricity from CCGT, coal, and a mix of the two.

Figure S4 and Table S4 present the carbon intensity of heat from fuel cells, with the reference technology being the average grid mix in the UK (as in Figure 10 of the main paper), and generation solely from gas, coal, and an equal mix of the two.

As with the results from the previous section, it is only under the most favourable scenario (from an electrification point-of-view) where electricity solely comes from CCGTs does the carbon intensity of heat from fuel cells approach that from ground source heat pumps, with PEMFCs averaging 130 ± 12 g/kWh and other technologies averaging 90 ± 10 g/kWh (not including the CFCL BlueGen). It is notable that even under this scenario, the CFCL BlueGen can produce negative-carbon heat, as its electrical efficiency is slightly higher than that of an average UK CCGT.

When fuel cells displace electricity from an equal mix of gas and coal (a crude estimation of the marginal generation mix), the carbon intensity of heat falls to –28 ± 26 g/kWh for PEMFC and –127 ± 35 g/kWh for other technologies (excluding the BlueGen). Every fuel cell model bar one produces negative-carbon heat, and in this case, the CFCL BlueGen reduces national CO2 emissions by 587 grams for every kWh of heat produced.

These results become more extreme when electricity is assumed to come solely from new coal power stations; however, this is as unlikely a situation as all power coming solely from CCGT.



Average UK grid mix (CI_{grid} = 510 g/kWh)

Average UK CCGT (CI_{grid} = 395 g/kWh)

Equal mix of gas and coal (CI_{grid} = 630 g/kWh)

Best possible coal (CI_{grid} = 860 g/kWh)

Figure S4: The carbon intensity of heat from fuel cells when displacing electricity from different sources.

Table S4: Carbon intensity of heat from fuel cells for different displaced electricity scenarios.

	Technology	System	Carbon intensity of displaced electricity (CI_{grid}) 510	395	630	860
A	PEMFC	EneFarm (Panasonic)	34	115	-48	-211
B	PEMFC	EneFarm (Toshiba)	39	119	-43	-205
C	PEMFC	GS EcoGener	47	137	-46	-229
D	PEMFC	Samsung RPG	63	142	-17	-177
E	PEMFC / SOFC	Callux (Vaillant, Baxi, Hexis)	74	135	12	-110
F	SOFC	EneFarm-S (Aisin Seiki)	-49	75	-176	-426
G	SOFC	EneFarm-S (Rinnai)	-33	91	-159	-410
H	SOFC	EneFarm-S (JX)	-8	101	-118	-337
I	SOFC	CFCL BlueGen	-303	-25	-587	-1149
J	PAFC	Fuji FP-100i	-8	91	-110	-310
K	PAFC	ClearEdge PureCell	12	100	-79	-258
L	MCFC	FuelCell Energy DFC	-19	82	-123	-328

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