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ANALYSIS OF FUEL CELL TECHNOLOGIES FOR MICRO-COGENERATION DEVICES IN THE HOUSEHOLDS AND SERVICE SECTOR

SUMMARY

Present-day fuel cells for combined heat and power (CHP), even when fuelled with natural gas, are a promising technology in residential and commercial sectors because of their efficiency and carbon benefits. Using micro-cogeneration devices in fuel cell technologies could play a significant role in reducing harmful emissions into the environment in the building sector at a national level. This paper presents different technological solutions for fuel cells in the building sector, and reviews their applications and their technical characteristics. These characteristics are the basis for their comparison with competitive low-carbon technologies. In addition, a common benchmark for comparison of different technologies through appropriate methodology is described, considering how these devices work when they are connected to an electric power system, while using real data of comparable devices.

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This paper presents evidence and methods required for comparison of fuel cells with conventional systems for production of heat and electricity, as well as for competing with low-carbon technologies. A common way to compare fuel cell directly to heat pumps is developed, primarily through calculation of the equivalent coefficient of energy efficiency. The intensity of carbon emissions from electricity production is calculated using replacement methods, and a logical extension for calculating the intensity of carbon emissions from production of thermal energy for comparison to heat pumps is proposed.

Key words: fuel cell, micro-cogeneration, households and service sector, combined heat and power

1 INTRODUCTION

The simultaneous production of electricity and heat using devices in fuel cell technology (hereinafter: fuel cells) is one of the most effective low-carbon ways of producing energy in the building sector today. For this reason, such a way of producing electricity and heat has not been adequately represented in energy plans, and in addition, discussions on sustainable production of thermal energy by using heat pumps which are powered by low-carbon electricity contributed to the slow development and application of fuel cells technology in the building sector [1, 2]. Despite its high energy efficiency and significantly lower harmful emissions to the environment, compared with other technologies, the prevalent view is that, since fuel cells are fuelled by natural gas, they represents a technology that can only be a bridging technology; therefore, it is another step on the way to "truly "sustainable production of heat and electricity [3,4]. This paper will present a simple and powerful method for comparing energy efficiency and carbon emissions intensity of fuel cells over competing technologies, such as internal combustion engines in cogeneration mode (CHP engines) and heat pumps that are powered by electricity or gas. It incorporates a high quality research that considered saving carbon emissions from those technologies [eg. 10-13], but done individually for each technology. Those studies that have dealt with the comparison of different technologies relied on significant simplification [2, 14-16] or carried out numerical simulations and load characteristics of buildings [17-20], which cannot accurately convey the real challenges and the diversity of life and business in buildings. This paper will present the latest data on the characteristics of certain technologies that replace par-declared characteristics of equipment with empirical data frame from the real use of different technologies. The focus is directed towards the research of fuel cell technologies since those technologies have the least amount of empirical operational data to date.

This paper will present two new general methods of comparing different technologies, namely: the equivalent coefficient of energy efficiency (COP), which has not been applied to fuel cell technology, and the intensity of carbon emissions in the production of thermal energy, which is largely neglected in relation to carbon emissions in the production of electricity. These methods can be used in any country and for different technologies without the need for corrective calculations, and can be used to confirm whether fuel cell technologies can produce thermal energy with greater energy efficiency than with the best heat pumps, and if so, can the heat produced be reasonably classified as carbon neutral or even carbon negative.

2 THE TECHNOLOGY OF FUEL CELLS AND THEIR CHARACTERISTICS

Fuel cells convert chemical energy into electricity and heat without combustion. A series of packages of individual cells are located in the device's heart, which are interconnected in order to ensure the desired power of the device. The cells provide a thorough conversion of hydrogen into electricity and must be interconnected with a number of auxiliary systems to ensure operation of the cogeneration system, including:

- The fuel processor that transforms natural gas or other fuels into hydrogen,
- Subsystem for the reception of heat and hot water production,
- Exchanger and a voltage regulator to convert DC to AC electricity and ensuring synchronization of alternating electrical energy to the electricity network to which the fuel cell is connected,
- Extra gas boiler in order to meet peak demand for heat energy,
- Control and security subsystems and others.

Most stationary fuel cells are fuelled by natural gas because of its availability and low cost compared to other fuels. Fuel cells can also operate on liquefied petroleum gas (LPG), kerosene and gas from renewable energy sources such as landfill biogas and other types of biogas from various types of plant and animal waste. If hydrogen was available using renewable energy sources, rather than hydrocarbons, fuel cells could be in a much more competitive position than other technologies, and thus would also:

- Halve the complexity of the system and its prices due to the removal of the fuel processor,
- Improve system efficiency by 15-20%.
- Transform fuel cells from being a technology in transition to being the main technology for low-carbon energy systems.

There are different types of fuel cells, depending on the type of material used and depending on the operating temperature at which they work, which results in the type of fuel that is accepted and auxiliary equipment that is required. However, all types of fuel cell technologies have high energy efficiency, very few moving parts, operate quietly and have low emissions. The four most common technologies in fuel cell cogeneration implementation used today in these sectors are: PEMFC - proton exchange membrane fuel cells (hereinafter: PEMFC), SOFC - solid oxide fuel cells (hereinafter: SOFC), MCFC - molten carbonate fuel cells (hereinafter: MCFC) and PAFC - phosphoric acid fuel cells (hereinafter: PAFC). Low temperature fuel cells in PEMFC technology, with operating temperature from 0 to 100 degrees Celsius, are the most advanced fuel cell technology, and represent about 90% of all fuel cells [23]. A decade of research and development of fuel cells resulted in their high efficiency and long lifetime, while costs fell significantly due to increased production [21]. High-temperature fuel cells in the SOFC technology, with operating temperature from 500 to 1000 degrees Celsius, are known for the greatest degree of electrical efficiency and greater flexibility to fuels, but cannot be operatively-dynamically managed as PEMFC technology can because of the high operating temperature [24]. Fundamental researches try to achieve the goal in the field of lifetime and stabilization of the temperature, with the trend towards medium temperatures from 500 to 750 degrees Celsius [25]. This would allow a wider range of materials that could be used, reducing production costs and improving dynamic characteristics. High-temperature fuel cells in MCFC technology are used for industrial cogeneration and power plants connected to the electricity system (3-60 MW), and become the leader in the market for large stationary applications [23]. Fuel cells in PAFC technology were the first such technology to be used for the production of thermal energy, and began being used in the 1970s in the service sector, in cogeneration systems [28]. Typical for fuel cells in PAFC technology is their long lifetime and high reliability, but also slightly lower efficiency than with other technologies [22].

2.1 Fuel Cells for Household Needs

Fuel cells for households in PEMFC and SOFC technologies are made up of a comprehensive system for heating and electricity supply, with a rated power of 0.75-2 kW of electric power and 1-2 kW of heat power, and are integrated into a unified energy system for household, together with a gas boiler and a hot water tank. The fuel cells systems are physically larger than gas boilers, typically located on the floor and installed outside the house or in the basement. The system weighs 150-250 kg and occupies two square meters of space, including a hot water tank and an auxiliary boiler, but smaller models are also being developed which can be mounted on the wall. Micro-cogeneration systems for household needs in large numbers began being installed in residential areas in 2009 in Japan. In 2012, for the first time, cogeneration systems in the technology of fuel cell cogeneration systems surpassed the technology of internal combustion engines with 28,000 sets built worldwide [31]. Leading manufacturers are Panasonic, Toshiba, Sanyo and Kyocera; CFCL; Baxi, Viessmann and Hexis; GM and FCPower. Japan leads in the implementation with 60,000 pieces of complete systems sold in the last four years [32]. Europe and South Korea are lagging behind Japan 6-8 years, but all regional markets increase around twice a year. This growth is expected to continue, and the Government of Japan plans to install 1.4 million fuel cells by 2020, while the European goal is 50,000 fuel cells, most of them in Germany [32, 33].

The program of the Japanese government, together with Japanese companies called ENE-FARM, has allowed the installation of over 120,000 units in households and is a good example of public-private partnerships in the development of new technologies. New models, which have arrived on the market in 2015, are smaller, more energy efficient, less expensive and a lot of them are easier to install than previous models. Models have also been developed for apartments and houses. The new models can be operated independently of the electricity grid; this is a reaction of the Japanese government to the concerns of end-customers about the reliability of the electricity grid after the events in Fukushima. Many companies in Japan participated in the development of new devices in fuel cells technologies, and among major companies that now produce commercial fuel cells for household are Panasonic and Toshiba, which offer market fuel cells in PEM technology, and

AisinSeiki that offers fuel cells in SOFC technology. Units in PEM technology have an extremely long life, with more than 60,000 hours in the pouring operation, which a few years ago was unthinkable. Panasonic claims that their model from 2015 achieved 95% of the overall energy efficiency. These units operate in parallel with the electricity grid, turning on and off in accordance to the demand for household electricity and heat. The result is the reduction of CO2 emissions in households up to 50% and reduction of costs of electricity from 60,000 to 75,000 Japanese yen. The intention of the Japanese Government for hydrogen technology is 1.4 million units for households by 2020 and 5.3 million units by 2030 (about 10% of Japanese houses).

The company called Ceramic Fuel Cells Limited (CFCL) is a world leader in the development of fuel cell technology that produces highly efficient and low-carbon electricity from natural gas. The CFCL company sells fuel cells in the SOFC technology in micro-cogeneration performance called BlueGen, which produces electricity from natural gas, to major energy companies and other customers in Germany, the UK, Switzerland, the Netherlands, Belgium, France, Italy, Poland, South Korea, Japan, Australia and the United States. CFCL is also developing fully integrated products for the production of electricity and heat with leading energy companies such as E.ON in the UK, GdF Suez in France and EWE in Germany. CFCL in February 2015 announced that their product called BlueGen achieved a leading electrical efficiency at a global level in an extremely wide load range. BlueGen fuel cell produces 1.5 kW of electricity with the electrical efficiency of 60% or greater, as shown in Figure 1 [5].

The green line is the standard electrical efficiency of BlueGen units, while the blue line represents the optimistic operating mode for improved BlueGen unit. With such improved operating characteristics, BlueGen unit achieves electrical efficiency greater than 60% within the operational workforce of 0.8 kW to 1.5 kW. The electrical efficiency greater than 50% is achieved already at 0.5 kW workforces or about 30% of its rated output power.

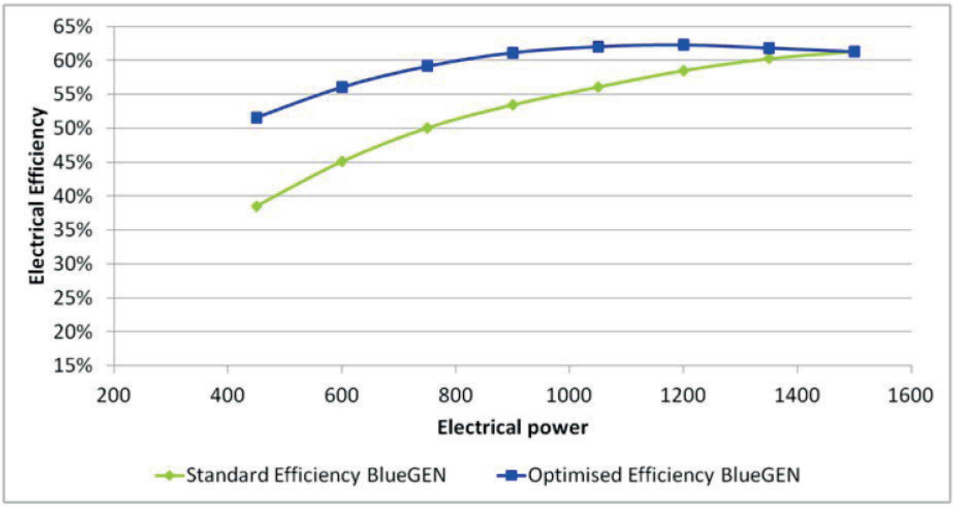

Figure 1: Electrical efficiency fuel cell BlueGen [5]

Such characteristics of BlueGen units will allow that the device operates in very harsh conditions, requiring the flexibility of the output of electric power, while maintaining high electrical efficiency within the declared operating mode. This significantly increases the commercial viability of production units in a variety of applications and different potential markets. A further focus of the development will be to reduce costs and to improve the production unit programs, and if possible, further develop of the characteristics of the commercial production units.

2.2 Fuel cells for service sector

Shops, offices, healthcare facilities and other commercial buildings used in the service sector are the next significant market for fuel cells in cogeneration mode [1.35]. The demand for thermal energy in a number of business premises has a lot smoother profile than consumption demand in individual houses and is therefore much more acceptable for fuel cell technology. Fuel cells for the commercial sector are in the electrical power range from 100 to 400 kW and typically operate in parallel with the existing system of thermal energy production. The development of stationary fuel cell is driven through various programs in the European Union (EU) countries, and so the year 2015 was recorded as the last year of the German program called Callux programme, a program that encouraged the development of fuel cells through several companies of the EU, primarily German companies. More than 500 production units have been installed all over the country through this program. Compared to a relatively large number of companies that have developed micro-cogeneration fuel cells in EU Member States, the number of companies that have develop commercial and industrial fuel cells is very small. A continuous collaboration is underway between EU companies and companies from the USA, Canada, Japan and China to develop new joint solutions for fuel cell of small, medium and large size. Examples include the company Fuel Cell Energy Solutions GmbH (FCES), which is part of the US Company Fuel Cell Energy Inc. Business, which imports the modules from the USA and then develops them into finished projects in Germany. Also, in July of 2015, FCES Company announced an agreement with E.ON Connecting Energies and Friartec AG for the delivery of 1.4 MW fuel cell in cogeneration mode for production plant of the company Friartec AG in Germany.

3 PERFORMANCE FUEL CELLS AND THEIR CHARACTERISTICS

3.1 Technical characteristics

Technical characteristics of the individual fuel cell technology and the individual performance of fuel cell are shown in Table 1. The values for electrical and thermal efficiency are reported for the net calorific value (LHV), and can be expressed in the gross calorific value of fuel (HHV) by dividing the values with 1,109 (for natural gas).

Table 1: Summary of declared technical characteristics of fuel cells [6]

Application		PEMFC	SOFC	PAFC	MCFC
		Residential		Commercial	
Electrical capacity	(kW)	0.75-2		100-400	300+
Thermal Capacity	(kW)	0.7-2		110-450	450+
Electrical efficiency a	(LHV)	35-39%	45-60%	42%	47%
Thermal efficiency a	(LHV)	55%	30-45%	48%	43%
System liftime	'000 h	60-80	20-90	80-1 30	20
	years	10	3-10	15-20 c	10 c
Degradation rate b	Per year	1%	1-2.5%.	0.5%	15%

[a] *Rated specifications when new which are slightly higher than the averages experienced in practice.*

[b] *loss of peak power and efficiency .*

[c] *Includes overhaul of the fuel cell stack half - way through life.*

3.2 Operational energy efficiency

Electrical and overall energy efficiency is relevant to cogeneration systems, but the major focus is on electrical efficiency since electricity is a much more valuable output of the system than are others. Fuel cells provide the highest electrical efficiency compared to any other technology that works in a cogeneration mode, and even small micro-CHP fuel cells are more efficient in relation to the best competitive conventional power plants [6].

Leading performance of fuel cell in the SOFC technology, for households, but also for those larger in size, have declared electrical efficiency of 45-60%, and the overall energy efficiency of 85-90% [7, 38]. The transformation of fuel for fuel cells PEMFC technology causes higher losses and lower electrical efficiency (up to 39%), but the overall energy efficiency is higher (95%) [8, 30]. Performance of European fuel cells for homes currently lags behind the leading Japanese and Australian models, with the current electrical efficiency within 30-35% for SOFC and PEMFC technologies [29].

Higher performance fuel cell PAFC technology has electrical efficiency at the level of 42% for electrical efficiency and 90% for the total energy efficiency [50], while fuel cells MCFC technology is at the level of 47% for electrical and 90% for overall energy efficiency [37]. Electrical efficiency is reduced during its lifetime due to degradation-decay of series of articles, resulting in an average electrical efficiency throughout its lifetime of 39% for PAFC technology and 42% for MCFC technology, while overall energy efficiency remains stable [39, 40]. Performance characteristics are in accordance with the manufacturer-declared characteristics since the building of the service sector provided largely continuous demand for energy.

System operation of fuel cell in real conditions in households, the achieved energy efficiency of small PEMFC and SOFC technology systems is less than the declared value, derived from laboratory tests, due to electricity for their own needs, because of reduced energy efficiency due to the load type, due to the energy required for starting the cycle of the device and loss of excess heat during the summer because of reduced demand [22, 29]. The general trend is that higher energy efficiency is achieved in homes with higher demand for thermal energy [41, 42]. The engines in cogeneration mode and heat pumps have similar experience when using the imperfections in households due to specific operational conditions [9, 43, and 44].

Table 2 provides information on electrical and overall energy efficiency of 11 performance fuel cells for households, information about how the system works in real conditions and the information provided by the manufacturer according to factory tests as part of the manufacturing process, which are declared data. Comparative data shows that the difference is about one-tenth compared to the declared default data.

Table 2: Electrical and overall energy efficiency of fuel cells under real operating conditions [6]

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

[a] *Electrical and total efficiency referred to as % el and % tot, against LHV.*

[b] *Referred to as "utilisation efficiency" or "capacity factor" to distinguish from gross generating efficiency under ideal laboratory conditions.*

[c] *Data is only available aggregated over three manufacturers of both PEMFC and SOFC.*

Fuel cells are characterized by very high energy efficiency at partial loads because the voltage series of articles increases with decreasing density. However, at the level of the overall system, reducing efficiency are caused by parasitic losses, which is why efficiency falls towards the real function, as shown in Figure 2. The individual performance of fuel cells differ depending on the type of series of articles: electrical efficiency falls much faster for SOFC technology, while thermal efficiency increases at partial load.

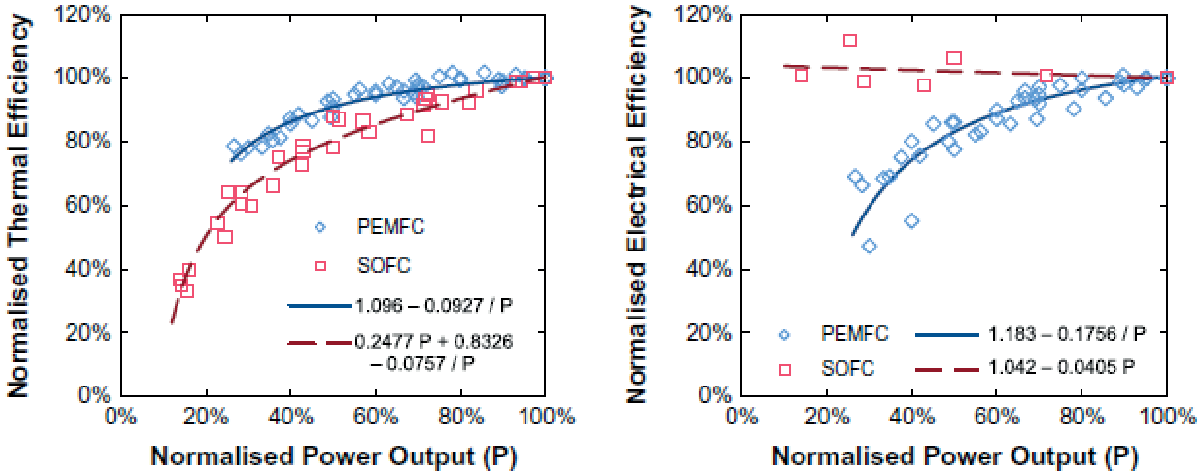

Figure 2: Electrical and thermal efficiency fuel cells for household [6]

3.3 The service life of the system

The duration of the system has been a key feature which slowed down the application of fuel cells and has been well below the critical 40,000 hours or about 10 years of work in household systems (about 5,000 h per year) [22]. System improvements in the last years were significant and so the lifetime values range as follows: Japanese fuel cell in PEMFC technology today guarantees 60-80,000 h of work [8, 30], and in SOFC technology up to 90,000 h [38]. Systems for households in Europe and other countries are trying to catch up with those standards, but the lifetime of their devices is around 10-20,000 h [29, 48].

The diagrams in Figure 3 show the improvement of the life of the system based on the manufacturer's warranty and results on the ground. Exponential growth characterizes each technology, suggesting the average industrial growth of the system’s lifetime of 16-22% per year since the beginning of the century.

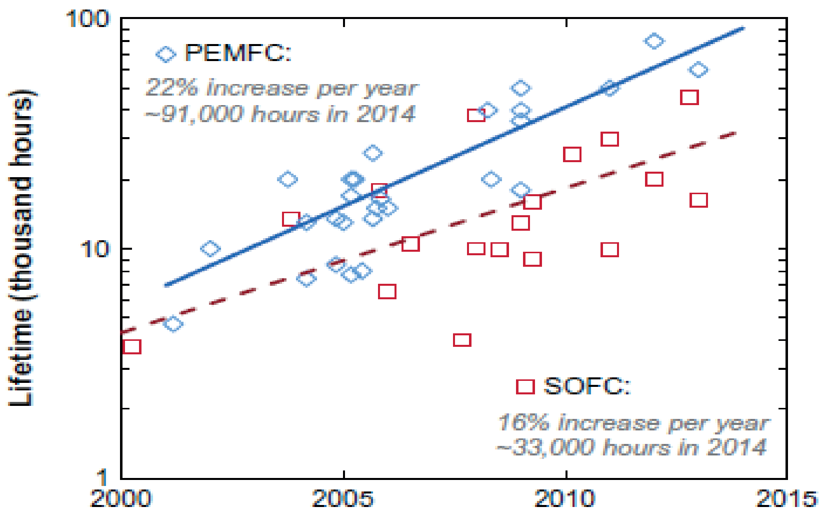

Figure 3: The service life of fuel cell PEMFC and SOFC technology [6]

Commercial fuel cells PAFC technology worked for decades, and the current system guarantees 80-130,000 hours (12 to 20 years, around 6,500 h per year), but with the need for outage after the first 10 years [52,76]. Fuel cells MCFC technology, on the other hand, is still battling with lifetime length due to aggressive chemistry of numerous articles and leakage [26, 49]. Since the system is expected to operate for 10 years, the average time for replacing a series of articles increases initial costs by about 15% [27].

3.4 System reliability

Conventional technologies for the production of thermal energy have a very high degree of reliability, approaching up to 99.9%, or about an outage every three years. Like all new technologies, fuel cell technologies are also struggling to achieve such a high standard. Fuel cell systems for household show a reliability of about 97%, according to a study conducted by Callux project tests in Germany. Mean time between failure (MTBF) is about 1,700 h (one failure every four months) [45]. MTBF has doubled since 2008 and the trend is expected to continue with the new generations. Similarly to that study, 90% of the unit from the first-generation project EneFarm suffered from failure in their first year during the period from 2004 to 2007, but these early problems were overcome and now only 5% of all systems fall short in the first years [8], which is comparable with the gas boilers. In both tests conducted, failures were distributed between the different components as follows: a series of articles, the converter of fuel circulation pump and system power management.

By reaching maturity, large fuel cells with PAFC and MCFC technologies moved to a higher level of reliability and their average value has been at 95% for more than a decade [27, 50]. This is the upper value that is achieved with conventional power plants [51], and is comparable with commercial engines in cogeneration mode [52].

3.5 Aging technology

All technologies suffer from deterioration characteristics over time, from gas turbines and wind turbines to solar photovoltaic panels [53]. But for the fuel cells this is a specific problem. Until recently, cell voltage falling was 0.5-2% per 1000 hours, which resulted in the decline of power output and electrical efficiency of 2.5-10% per year [22]. This problem is partially replaced by increasing the thermal efficiency as losses of energy transformed into heat energy.

In the previous period, the level of aging is reduced to 0.5-1.5% per year in leading PEMFC and PAFC technologies [29, 54], 2% per year in MCFC [27] and 1.0 to 2.5% per year in SOFC technologies [46, 55, 56]. End of life is often proclaimed if output falls 20% below the rated power, which nowadays happens after 10-20 years of operation.

4 ENERGY PERFORMANCE OF COMPETING TECHNOLOGIES

Energy sector is a sector with rapid changes and characteristics of various technologies are constantly improving, which means that comparative technology must be based on the most recent and reliable data. It also declared that the production characteristics are not necessarily representative of the real operating conditions of complete systems. Three technologies are competing with the technology of fuel cells on the market for households and service sector: internal combustion engines in cogeneration mode, and heat pumps driven by electricity or gas. The thermal energy obtained from biomass is the fourth option, but assessing energy efficiency, practicality, and sustainability of different options, requires a special in-depth assessment [34, 57 and 58].

4.1 Internal Combustion Engines

Internal combustion engines in cogeneration mode are less energy efficient than fuel cells due to the losses in the conversion of heat energy into mechanical or electrical energy, although thermal efficiency increased as a result of the conversion. Engine from the manufacturer Honda, model Honda ECOWILL is the most effective model for the size needed for the household (26% electrical efficiency, 66% thermal efficiency) [59]. Electrical efficiency grows with the capacity by using large cylinders, low-speed engines with higher compression [60]. Systems for domestic and small service business premises (1 power 10 kW) achieved electrical efficiency of 25-30% of net calorific value of natural gas, followed by 30-35% for larger service premises (power 20-200 kW) and of 36-40% for industry and energy companies (power of 0.5-5 MW) [52,60,61]. Thermal efficiency drops with time and much faster in the rated capacity, which means that the total energy efficiency fall is in the range from 85-92% to 73-84%. Results from independent laboratory testing show that the electrical efficiencies are close to the values that are declared by the producers; however, the overall energy efficiency is about 5% smaller [62]. At least three field tests have shown that these characteristics are similar in the building sector, provided that there is a consistent demand that will allow many working hours [12, 63 and 64].

External combustion and Stirling engines have similar overall energy efficiency but significantly lower electrical efficiency of around 12-18% for households and 20-25% for larger service areas [61]. However, several studies have shown electrical efficiency of only 6-10% if the technology is very sensitive to the working conditions and working hours [12.65-67]. Small houses recorded small electrical efficiencies, where electricity produced is less than the consumption of the system control unit [12].

4.2 Heat pumps on electric power

Heat pumps are characterized by their heat pump coefficient of performance (COP), which is obtained by dividing the quantity of heat provided by the electricity used to operate the pump under certain specified conditions. The values of the coefficient often moves within the value of 3 or 4, and in some practical research in households, as well as demonstration projects, the values obtained are in the range from 3.0 to 3.5 for a heat pump with air as a heat source (ASHPE) and 3.3 -4.2 with ground source heat (GSHP) [9]. However, the characteristics depend strongly on the temperature of the heat collectors, the outside air temperature for ASHPE or temperature below ground or water for GSHP, while the coefficient of efficiency is reduced by 0.1 for every one degree Celsius fall of the outside temperature [9].

A better measure of efficiency is therefore seasonal coefficient of performance (SPF), which represents an annual coefficient of efficiency of the heat pump for a particular location, counting the temperature changes throughout the year [9]. SPF also account for the amount of energy used for circulation pump and auxiliary heating (as heat pumps normally have as a backup option resistive heating to electricity for peak loads) [9, 68].

In large practical researches in Germany, for systems of heat pumps of ASHPE type installed in households, the average seasonal coefficient of efficiency, on an annual basis, was measured in the range of 2.6 to 3.0, while the systems of heat pumps type GSHP achieved an average SPF of 3.3-4.0 [69, 70]. Two studies in the UK achieve the SPF value of 2.4-2.6 and 3.0-3.2 for ASHPE for GSHP [99,100], which is lower than the results in Germany due to colder and wetter climate in the UK, and due to certain problems which are caused by the installation, sizing system and mode [71, 72]. Heat pumps are particularly sensitive to work conditions and need more trained installers to achieve standards as prescribed in Germany [9].

4.3 Heat pumps with gas

Two technologies of heat pumps prefer to drive using gas rather than electricity. Heat pumps that use gas internal combustion engines to power the compressor, which exploit waste heat from the cogeneration process by which electrical energy is produced [73-75]. Gas engines also power the heat-driven adsorption and absorption reactions, using chemical reaction of water-ammonia and zeolite instead of vapour compression cycle [73-75]. Although small engines are less energy efficient than electric power units, processing of waste heat increases the overall output efficiency to 30%, which is especially useful in colder climates [75, 76]. Unfortunately, data on the effectiveness of the field is not available.

5 TEMPERATURE DEPENDENCE OF FUEL CELL

For fuel cells and other technologies, the quantity, and efficiency of heat output falls as temperatures rise. Air/water of higher temperature has higher energy content and therefore cannot be produced in an efficient manner. The decline is minimal conventional technology because the flame temperature in a combustion engine is a few hundred degrees Celsius, while in other technology without burning the drop is even higher. This is most evident with heat pumps that rely on the temperature difference between ambient temperature and heat that provides for the needs of the household.

Figure 4 shows data from a variety of tests on the ground and different variations of different technologies. The average levels of efficiency losses are:

- 1-2% for 10 degrees Celsius at the micro-CHP system;
- 6-9% for 10 degrees Celsius with micro-CHP fuel cell;
- 14-19% for 10 degrees Celsius with a heat pump.

This highlights the importance of using low-temperature heat distribution for space heating applications and explains why high-temperature industrial processes are the hardest for decarbonisation.

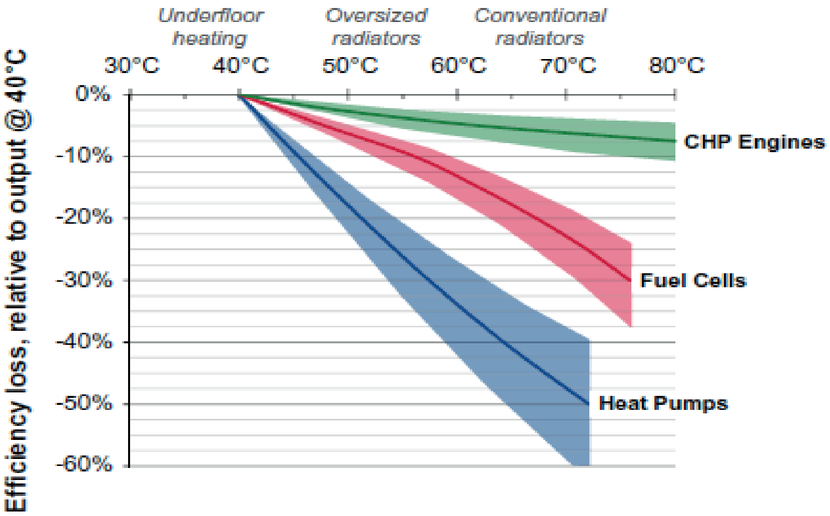

Figure 4: The influence of the outside temperature on the efficiency of thermal energy [6]

6 METHODS OF COMPARING ENERGY EFFICIENCY OF DIFFERENT TECHNOLOGIES

6.1 Comparison of efficiency through technology

Comparing the efficiency of fuel cell devices with other low-carbon technologies is not easy due to their structural diversity. For example, heat pumps consume electricity, while technology operating in cogeneration mode producing electricity. It is necessary to properly define the values of energy efficiencies, as electrical and thermal efficiency are used for cogeneration systems, and the coefficient of energy efficiency is used for heat pumps, providing a ratio of thermal energy that we get and the electricity that we provide.

MacKay explained in [3] that there is no simple cogeneration system which can be compared with the characteristics of the heat pump, which produces 3-4 units of heat per unit of electricity. This is acceptable for a medium-efficient cogeneration engine, but not for fuel cells. These technologies in different countries may be compared by calculating the electrical opposite the thermal efficiency in order to show their differences as in [3]. Primary energy efficiency of the heat pump depends on the heat pump and electricity used for its operation. The most efficient gas turbine with a combined cycle (CCGT) works with the gross energy efficiency of 60% [77], but its own parasitic consumption and time wear reduces the efficiency by 7% [53], while further transmission and distribution losses bring an additional 7% reduction of the efficiency, in the example of the UK [78]. In the last five years, a group of gas CCGT type power plants achieved an average net efficiency of 52%, which implies efficiency from the burner to the load port in the socket [78].

6.2 The calculation of the equivalent coefficient of energy efficiency for the system with fuel cell

By adopting measures that are used to determine the energy efficiency of heat pumps, different methods for comparison of different technologies can occur, which are based on the following ratio of input and output values in the energy system: the ratio of heat output and the amount of energy used at the entrance of a given energy system. Li et al. was the first to introduce the COP for cogeneration turbine of a large sizes [118], calculating the amount of electricity that is not produced when it products only electricity in relation to cogeneration mode [79]. Lowe then introduced a similar method of determining the energy efficiency of cogeneration plants [120], and considerations of this problem by MacKay, which are used in the Heat energy strategy of the UK [80]. These methods are suitable for high power, such as 100 MW cogeneration power plants, but they cannot be applied to electrochemical systems such as fuel cells, which can not only produce electricity. The development of the new method is based on the adaptation of this concept to fuel cells, considering the process of enlargement of the systems which is used in lifecycle assessment methodology (LCA). By extending the model onto the entire electricity sector, the COP equivalent for the fuel cells could be calculated by dividing its heat output by the electrical output which was realized in the consumption of gas in the fuel cell (probably much more energy efficient), instead of in the CCGT power plant (best alternative technology) .

Equivalent COP is calculated from the thermal efficiency fuel cell (η_{heat}) divided by the difference between the electrical efficiency of fuel cell (η_{elec}) and electrical efficiency of alternative power (η_{CCGT}) that is extra electrical power that can be generated by the gas used in the gas plant instead of the fuel cell:

$$\mathrm{Eq}_{\mathrm{COP}} = \frac{\eta_{\mathrm{heat}}}{\eta_{\mathrm{CCGT}} - \eta_{\mathrm{elec}}} \qquad (1)$$

6.3 The calculation of the intensity of carbon emissions to the generated heat and electricity

By producing electricity and heat at the point of consumption, the fuel cell in the cogeneration process achieves significant CO_2 emission savings compared to centralized produced electricity and conventionally produced heat energy. There are several methods for determining the value of carbon emissions of the produced electricity in the cogeneration process, as the total emissions from the system must be allocated between the output value of electricity and heat [60, 81]. A typical fuel cell emits 500-600 g of CO_2 while producing 1 kWh of electricity and 1.5 kWh of thermal energy. These emissions can be assigned to each output product equally, weighted by its economic value or estimating net emissions by requiring the production of a single output of the product [82].

For example, if 1.5 kWh of heat is not produced using a fuel cell, it may be created using a different technology, so-called "reference technology". The common method for the allocation of the reference technology is therefore to assess how much fuel reference technology will spend to deliver such a large amount of heat energy, and take away the resulting amount of fuel consumption of the fuel cell in order to get the net amount of fuel that is used solely to produce electricity.

Similarly, the intensity of carbon emissions for electricity produced can be calculated by assigning production of heat in the cogeneration process with an avoided production of thermal energy by using a condensing boiler. The intensity of carbon emission fuel cell to produce electricity is equal to the total amount of carbon emissions due to the production of one kWh of electricity reduced emissions that are avoided due to the simultaneous production of thermal energy. The total amount of emissions is equal to the intensity of carbon emissions flare gas (C_{fuel}) divided by the electrical efficiency of fuel cell (η_{elec}). Avoided carbon emissions are equal to the intensity of carbon emissions due to the replacement of produced heat (C_{boiler}) multiplied by the amount of generated heat with each produced kWh of electricity, which gives the ratio of thermal efficiency (η_{heat}) and electrical efficiency of fuel cell.

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

The method of equation (2) is relatively standard, used in the US EPA as a measure of "effective electrical efficiency" [60] and promotes commercial cogeneration systems [50, 37]. Less widely discussed indicator measuring the intensity of carbon emissions due to the production of thermal energy, in contrast to the intensity of carbon emissions due to electricity production. The only real application of these measurement indicators is the government standard procedural assessment of the UK when calculating the emissions of CO_2 when heating in local communities [83], as well as a special option for the calculation of emission factors for the offered heat or steam [81]. This method is not suitable for individual cogeneration plants or micro-cogeneration, and has not raised great, if any, attention in the academic literature. The equation (3) gives the calculation of the intensity of carbon emissions for the production of thermal energy:

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

The intensity of carbon emission fuel cells for the production of thermal energy C_{FC}^{heat} is equal to the total emissions to produce one kWh of thermal energy less emission avoided due to the simultaneous production of electricity. Total emissions are equal to the intensity of carbon emissions of gas divided by the thermal efficiency of fuel cells and the emissions that are equal to the intensity of carbon emissions for electricity from the power supply (C_{grid}) multiplied by the amount of electricity that is produced by one kWh of thermal energy.

Impartially speaking, it is estimated that usually the best standard and available technology is the gas water heater. The intensity of carbon emissions of natural gas was 205 g/kWh (LHV), and the latest condensing boilers with an average of 94 ± 4% of energy efficiency, in real conditions of use, produce thermal energy with emissions of 218 gCO_2/kWh [44, 84].

6.4 The importance of the production of the average and marginal electricity

The intensity of carbon emissions due to electricity generation from the mains is open to evaluation because it is different from country to country, dependent on the season and time of the day. In the UK, the central electricity production has an average intensity of carbon emissions in the range from 500-520 g/kWh [78]. However, the average intensity varies over time as the energy-mix plants in operation (on an hourly basis) change in relation to the demand for electricity. Emission intensity is lower during the night, since nuclear power plants work in an almost constant operating regime with regard to power, which means that the fossil fuel plants reduce their work strength or shut down.

That's why we use the marginal emissions rather than the average ones when calculating the impact of distributed electricity generation. Changes in demand for electricity, caused by heat pumps that use electricity or fuel cells that generate electricity, will not cause the same reaction in the planning of power plants in the electricity system (EES). Some plants in the power system are not flexible to change of power (nuclear) or are largely unpredictable regarding the labour power (wind), leaving the remaining gas, coal and hydro power plants, which can be used to react to changes in the demand. Typical power plant (a combination of power plants) which can be engaged in response to changing demand, is known as the marginal plant, and connected with that is the marginal emission intensity which determines the actual reduction of emissions of CO_2. While the intensity of average emissions in the UK is around 510 g/kWh, the intensity of the marginal emissions had an average of 690 g/kWh from 2002 to 2009 [85], and 640 g/kWh from 2009 to 2012 [127], which is around the mean between CCGT-gas plant (410 g/kWh) and coal plants (950 g/kWh) [34]. Determining the value of marginal emissions is a controversial issue and that is why average emissions are used in order to obtain the central results in this research.

7 THE RESULTS OF THE RESEARCH

7.1 Comparison of energy efficiency fuel cells and heat pumps

Figure 5 shows data on energy efficiency for conventional and low-carbon systems listed above, which are based on the characteristics of individual devices in real operating conditions, facing given producer characteristics.

Conventional - traditional systems were first presented as follows:

- Electricity from an average combination of power plants (according to data from the UK with 38.6% energy efficiency [78]), and the heat from the condensing boiler (94% energy efficiency [44]);
- The conventional - traditional technological limit is connected with a dashed line, whose technologies must be surpassed in order to offer a minimal improvement of energy efficiency.

Then "the best" low-carbon systems are considered, as follows:

- Electricity from the most efficient power plants (CCGTs with 52%) [78], and thermal energy from heat pumps based on the underground energy sources installed in accordance with the highest standards (COP 3.3 to 4.0) [69,70];

- Intersection of technologies that use electricity is increased by efficient CCGT power plants, such as the COP 4 for heat pumps which produces 2.08 units of heat energy from one unit of natural gas burnt in the CCGT;
- The green line that connects all of these points is the limit of electricity, which represents the best available set up low-carbon solutions of the best energy efficiency, while shaded areas cover potential heat pump based on underground sources of energy, energy efficiency seen in a real use.
- Finally, the energy efficiencies of cogeneration systems that use gas are shown:
- Cogeneration with motors from 1 kW to 5 MW [52, 60, 61], with the overall efficiency reduced by 5%, which was used in the calculation in order to increased losses of the devices tested in real working conditions around the world [12, 62];
- Fuel cells based on the characteristics of real use systems around the world shown in Table 2.

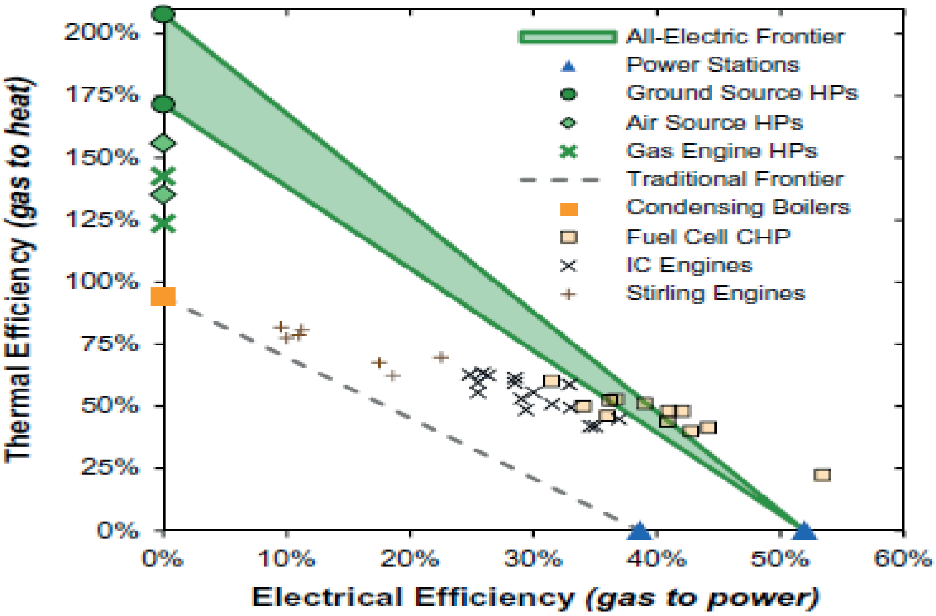

Figure 5: The energy efficiency of different technologies under real operating conditions [6]

As expected, all forms of low-carbon heating exceed the characteristics of the gas condensing boiler. The engines in cogeneration mode and gas heat pumps are slightly below the low-carbon limit, according to the MacKay, and have a similar performance compared to the current heat pump based on energy from the ambient air. However, fuel cells are around or above the threshold, implying that the best fuel cells (SOFC and MCFC generally) are much more efficient than the best heat pump even when these heat pumps are supplied with the most power from the mains.

In practice, it is not possible to guarantee that the heat pump be powered solely from a CCGT type power plant, a combination of power, gas and low efficient coal, usually covering marginal power they can act in response to changes in demand [85]. Less optimistic assumption can move the entire border electricity on the left in Figure 5 (as production efficiency falls).

7.2 The equivalent ratio of energy efficiency fuel cells

Continuing with the assumption that centralized power plants are composed only of type CCGT power plants, with a 52% energy efficiency, equivalent COP for fuel cells PEMFC technology ranges from 2.8 to 3.4, and for PAFC and MCFC technology ranges from 4.1 to 4.8, while the best Japanese SOFC technology reaches 5.3. The system with a fuel cell called BlueGen of CFCL is equivalent to the heat pump with infinite COP, since its electrical efficiency is greater than the gas CCGT power plant and delivers useful heat. For comparison, the CHP engines shown in Figure 5 have an equivalent COP of 2.3 to 2.8, which is lower than both heat pumps, based on the energy in the air from the environment and energy from the ground [3]. Equivalent COP depends on the effectiveness of both the fuel cell and the power plant used instead of it. Figure 6 shows this sensitivity to a variety of fuel cell technologies. If fuel cells are replaced by the power, in equal parts, from the CCGT plant type (52% efficiency) and from standard coal boilers (40% efficiency), the equivalent COPs are significantly higher: 4.3 to 5.5 for PEMFC; 8.4 to 12.0 for PAFC and MCFC; and 14.4 - infinity for SOFC.

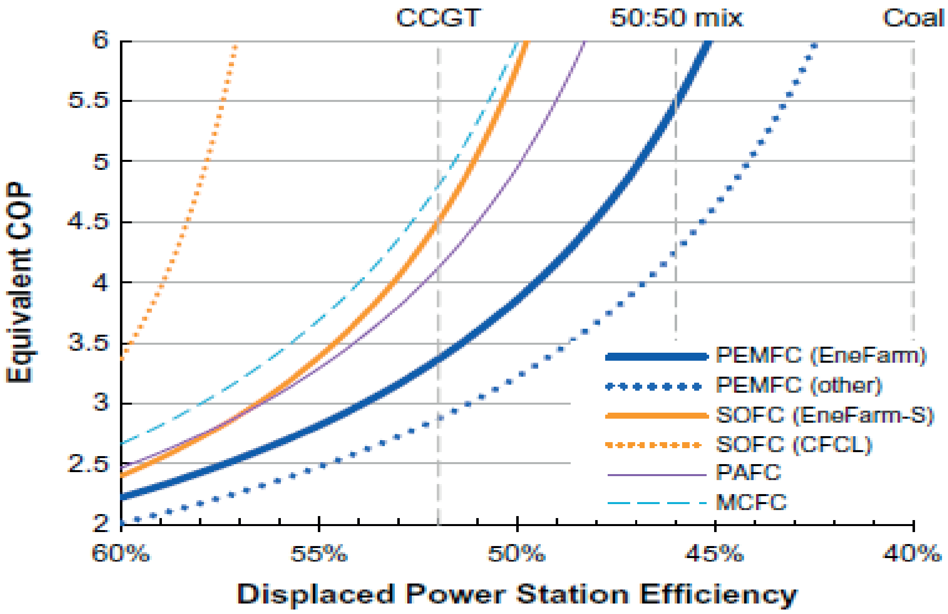

Figure 6: Sensitivity equivalent COP fuel cell on the electrical efficiency of the power system

Equivalent COP is a very sensitive characteristic of the fuel cell since the two conditions from the denominator (η_{CCGT} x η_{elec}) in the equation 1 are extremely close in value. Table 3 shows how the equivalent COP grows when declared efficiency is used in the area of real characteristics, calculated according to 52% efficient CCGT type power plants. As an example, we can take a 5% difference in relation to the declared data on energy efficiency to the experience of Aisin Seiki EneFarm-S [46, 47], which reduces its equivalent COP of 8.0 to 5.3, according to Table 3.

Table 3: Equivalent COP for fuel cells with 52% efficiency power system [6]

	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
AisinSeiki & 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

7.3 The potential for mitigating carbon emissions

It is very difficult to generalize about the absolute savings of CO $_2$ derived from the use of fuel cells as they vary from country to country, mainly due to the intensity of carbon emissions from centralized power plants in the electrical network [86]. In Japan and Germany, manufacturers advertised 0.7 to 1 kW systems that generate savings from 1.3 to 1.9 TCO_2 per year in households with four members (reduction of 35-50%) [8, 30, 38, 129], while 1.5 kW CFCL BlueGen in Australia saves about 3 tons per year [7]. Slightly larger commercial systems (350-400 kW) offer savings of 700-1300 tCO_2 per year in Germany and the United States [27, 50]. There has been a general consensus that in countries with a common power system that is rich in carbon emissions, fuel cells (depending on the technology) can realize savings from 1.5 to 2 tons of CO_2 per year per kW of installed capacity. In other low-carbon technologies (e.g. photovoltaic panels and nuclear power plants), these savings can be additionally balanced with respect to carbon emissions generated during the production and/or construction of the power plant. The savings of carbon emissions for fuel cells are larger and more significant than for gas boilers that replace and require catalysts of nickel and platinum, which are extremely energy-intensive to produce.

Several lifetime estimates have taken into account the estimation of these carbon emissions, known as carbon footprint, discussing how fuel articles are produce, how much energy and which materials they require and how these materials are produced. The production of 1 kW cogeneration system for household emits 0.5 to 1 TCO_2, while a 400 kW commercial system emits 100 to 400 tons of CO_2 [86,87-90]. If we reduce these emissions to average values by lifetime of those systems, they range from 10-20 gCO_2 per kWh (g/kWh) for electricity generation or 8-16 g/kWh of thermal energy production [86]. For comparison, the intensity of carbon emissions during construction is widely estimated at 40-80 g/kWh for photovoltaic sources of electricity and 10-30 g/kWh for nuclear power plants, from which we can conclude that the fuel cells technology has a relatively low environmental impact.

7.4 The intensity of carbon emission fuel cells in the production of electricity

To avoid ambiguity caused by the diversity of national combinations of power plants to produce electricity, we can calculate the intensity of carbon emissions (g/kWh) instead of the absolute emission reductions. It then depends only on the characteristics of the fuel cell and heating system which it replaces. When the thermal energy is supplemented from the condensing gas boiler, then the intensity of carbon emissions, due to electricity from the fuel cell, is in the range from 240-280 g/kWh for the combination of about 2/3 CCGT plant type and ¼ coal plant. Electricity from fuel cell has therefore significantly lower emissions than even the average or marginal emissions of power plants in most national electricity systems. The above values are based on the operational energy efficiency from the real conditions of use, and if the declared value were used (without penalization shown in Table 2), the intensity of carbon emissions would fall to 215 - 265 g/kWh.

Taking as an example the Panasonic EneFarm model that is in use in Japanese homes, η_{elec} = 36.7% and η_{heat} = 52.6%. For every kWh of electricity produced, 2.73 kWh fuel is consumed and 559 gCO_2 is emitted. Fuel cell also produces 1.43 kWh of thermal energy, for which, otherwise, 1.52 kWh of gas would need to be burned in a condensing boiler, and therefore the emissions would need to be reduced by 313 g. Therefore, the net intensity of carbon emissions is 246 g/kWh, which is similar to the one for fuel cells with PAFC technology (225 g/kWh) and fuel cells with MCFC technology (238-308 g/kWh) [36, 37].

Figure 7 shows the intensity of carbon emissions as a function of their electrical and thermal efficiency, showing fuel cells in parallel with an internal combustion engine (which averaged 255 to 315 g/kWh) and Stirling engines (240-340 g/kWh). There is considerable overlap between the intensity of carbon emissions from the electric power of each technology and electrical and thermal efficiency that are nearly balanced in a ratio of 1:1.

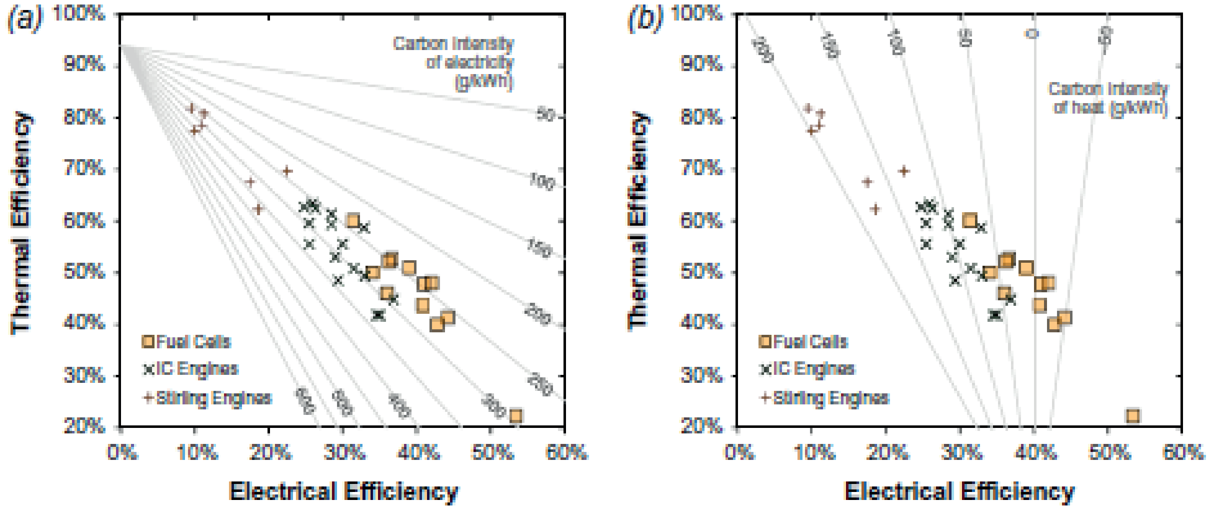

Figure 7: The intensity of carbon emission fuel cells and other technologies when the heat is replaced from condensing boiler and electricity from the power system UK

7.5 The intensity of carbon emissions due to heat from the fuel cell

If electricity from fuel cells is responsible for escaped centralized electricity production, the intensity of carbon emissions due to the resulting thermal energy is around zero in the UK. Using the previously mentioned example, PEMFC fuel cell technology produced 1.43 kWh of thermal energy, emitted into the environment 559 g of CO_2, while simultaneously producing 1 kWh of electricity and reducing national emissions of CO_2 to about 510 g/kWh (with an estimate of the average network energy mix); therefore, thermal energy has a net carbon intensity of 34 g/kWh (559x510/1.43), which means a six times increase compared to modern condensing boilers. By repeating the calculation with a much more efficient AisinSeiki SOFC (η_{elec} = 44.2% and η_{heat} = 41.3%) outputs thermal energy that is carbon negative, with the intensity of -49 g/kWh.

It may seem counter-intuitive that a technology that uses fuel gas can produce thermal energy that is carbon neutral, but it is possible if electricity with lower emissions than emissions in the electricity grid is produced, and the thermal energy is also being used and is not thrown away. Any technology with gas combustion, with the electrical efficiency greater than 40%, has a lower emission than the average emission in the electricity grid of Great Britain; therefore, fuel cells SOFC and MCFC technology also fall into that category, while fuel cells PAFC and better PEMFC technology are not so far behind. Figure 7b shows the intensity of carbon emissions of heat from cogeneration systems whose values are: fuel cells emission average from -110 to 85 g/kWh; internal combustion engines from 70 to 120 g/kWh; Stirling engines from 155 to 200 g/kWh. For comparison, due to heat generation from heat GSHP type pumps, which use electricity exclusively from CCGT plant type, emit an average of 100 to 120 g/kWh, with an increase to 130 - 150 g/kWh for ASHPE type heat pump. If the heat pumps were to use electricity with the average formation of power plants in the UK, data on emissions for those heat pumps would be greater by 30%.

Fine lines in Figure 7b move to the right if the intensity of carbon emissions from the grid for electricity produced fall, reducing the attractiveness of cogeneration gas. If the network carbon emissions were to be halved to 255 g/kWh, then the electricity from centralized production would become equally valuable to the one produced from cogeneration technologies, as calculated in the previous section. The intensity of carbon emissions of heat from all cogeneration technologies would then converge towards the values that were obtained for burning gas in condensing boilers; then cogeneration would no longer provide benefits in carbon emissions. It is expected that the average carbon emissions in Great Britain's network, according to the latest calculations of carbon emissions, would fall to that level in the early 2020s, but it should be remembered that one cannot expect that the intensity of the marginal emissions would fall below 400 g/kWh (due to modern CCGT plant type) until the question of flexibility and manageability of low-carbon technologies is resolved.

8 FINDINGS

A global review shows that the demand for heat energy rises to the level of half of the total energy consumption and CO_2 emission, but the reduction of carbon emissions in the production of thermal energy attracted relatively little attention compared to electricity and transport [4]. Since many countries are using gas for heat production in a highly-efficient way, it is still not yet a cost-effective low-carbon alternative. Fuel cells are not highly emphasized in the EU Decarbonisation Strategy, and are still losing against heat pumps.

This paper provides evidence and methods required for comparing conventional fuel cell systems for heat and electricity production and for competing with low-carbon technologies. A common way to compare fuel cells (and other cogeneration technology) directly to heat pumps is developed, primarily through calculation of the equivalent coefficient of energy efficiency. The intensity of carbon emissions for electricity production is calculated using replacement methods, and a logical extension is proposed in order to calculate the intensity of carbon emissions for the production of thermal energy for comparison with heat pumps.

Currently, the best solutions in the fuel cell cogeneration mode for the needs of households and the service sector, which made the analysis, reveal some key points:

- Electrical and thermal efficiency are declaratively large, but when the system works in real conditions, frequently switching the device on and off, then these values are different,
- Energy efficiency demonstrated in households is up to 10% less than the declared values, which reflects very similarly with the experience gained with heat pumps and engines in cogeneration mode,
- The service lifetime and reliability are significantly improved by the standards of competitive micro-cogeneration technology.

Even with optimistic assumptions that all electricity is produced from highly energy efficient CCGT type plants, equivalent COP fuel cells range from 2.8 to 5.3, and for the system with the best features, such as fuel cells with SOFC technology, the equivalent COP is infinite, since fuel cells with SOFC technology require less gas to produce electricity than CCGT type power plants would; and, in addition, it additionally provides thermal energy as an additional benefit. When the average energy mix for the UK was being considered (which is a distinctive energy mix for a country of higher national income), the equivalent COP grew to between 4 and 14, significantly higher than is achievable with electric or gas-powered heat pumps.

The intensity of fuel cell carbon emission can be summarized as follows:

- The equivalent thermal energy from a condensing boiler and electricity from the UK mains, with an average energy mix (two-thirds of the best CCGT power plant), is produced with half the intensity of carbon emissions from fuel cells; or
- Electricity from the power network of the UK with an average energy mix and heat energy that is carbon neutral or even carbon negative.

The development of common criteria for the comparison of different technologies, and respecting how they work within the interconnected power system, shows that the fuel cells provide heat with a higher energy efficiency than can be obtained with the best heat pumps and the heat leads to equal or even net reduced national emissions of CO_2 from the use of electricity from the electricity grid, which has a higher carbon emission. Efforts to de-carbonise the power system with renewable energy sources and nuclear power plants will not significantly affect these conclusions since renewable energy sources can still quickly and easily respond to changes in demand, and are not likely to ever become marginal sources of electricity.

Fuel cells with the best characteristics in terms of energy efficiency should undoubtedly be treated as carbon neutral technologies for thermal energy. Just as heat pumps are classified as renewable technologies, despite consuming electricity from the mains, the same logic can lead to the claim that the most efficient fuel cells can be classified as renewable energy, despite consuming natural gas. So far, fuel cells have been excluded from these discussions, and as an example the definition of renewable heat in the EU directive for renewable energy can be used, which includes an electrical energy heat pump from the electricity grid, which has high carbon emissions, but excludes cogeneration systems that can offer similar or better value energy efficiency and lower carbon emissions.

There is a strong opportunity for fuel cells to contribute to low-carbon heating worldwide, by combining high efficiency, large annual energy output and wide applicability in building sector. Fuel cells can play a major role in national decarbonisation and energy policy strategies which should ensure access to this promising technology [4].

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