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A Case Study Analysis of System Efficiency, Viability and Energy Values of SOFC Based Fuel Cell Micro-CHP for Office Buildings

Alem Tesfai[a], Anastasia Mylona[b], Paul Connor[b], Mark Cassidy[b] and John T. S. Irvine[b]

[a] KTP Associate Chartered Institution of Building Services Engineers (CIBSE)
222 Balham High Road, London SW12 9BS, UK
[b] School of Chemistry, University of St. Andrews, Fife KY16 9ST, St. Andrews, UK

The built environment is a large contributor to the greenhouse gas emissions. The first step in tackling environmental impact and fuel cost reduction is the minimization of energy losses through introduction of new and more efficient energy conversion technologies. In this study, the potential application of fuel cell micro-CHP in a typical office building is investigated. A 1.5 kW_{el} fuel cell micro-CHP has been installed in an office building at CIBSE headquarters (HQ). The unit converts natural gas to electricity, using Solid Oxide Fuel Cell (SOFC) stack. The installation and data from the operation of the system is discussed. The data shows that the heat recovered from the SOFC stack covers most of the domestic hot water requirement of the office building, requiring minimal top-up from the immersion heater.

Introduction

In recent years, due to increasing energy demand and in order to mitigate its impact on the environment, the search for reliable, sustainable and affordable energy sources and new technologies to increase energy efficiency has intensified. The built environment is a large contributor to the greenhouse gas (GHG) emissions [1,2]. The commercial and domestic buildings consume about 45% of total energy consumption in the UK [3]. New building regulations, such as Part L 2013 and the European Buildings Directive [4,5], require engineers to minimizing energy losses by introducing improved insulating materials and energy efficient technologies such as Combined Heat & Power (micro-CHP) systems [2].

Micro CHP can be described as a small scale power station that can be installed in residential or commercial buildings to generate heat and electricity on site. The simultaneous production of useful heat and power within the building is more efficient than most sources of grid electricity because it eliminates the heat and transmission losses. The heat generated during electrical production can be recovered and used for domestic hot water requirements or for space heating resulting in reduced carbon emissions. Several technologies have been put forward for micro-CHP systems including Stirling engines, internal combustion engines and fuel cells. A review of micro-CHP technology in general and fuel cell-micro-CHP in particular is extensively discussed and the findings presented in [1,6]. Fuel cells generate electricity more efficiently than other micro-CHP technologies such as Stirling or internal combustion engines which generate electricity at only 15 to 30 percent efficiency, and so produce relatively more heat.

However fuel cells are less mature than these engine technologies, and are therefore more expensive and less durable [1]. The Heat to Power Ratio (HPR) of a house varies significantly with time [7]. While there are several methods available to dynamically change the HPR of the fuel cell, currently SOFC based micro-CHP cannot match the highly variable and unpredictable energy demands of a typical house. Therefore this case study looks into the potential application of fuel cell micro-CHP in a typical office building with a high base load demand. With the current fuel cell technology, the use of such systems in office buildings has the potential to be more efficient and reliable than in a single family home where the electrical power demand varies from low level during the day to spikes of several kilowatts in the evenings. This case study aims at developing an optimised SOFC micro-CHP system for CIBSE HQ office building.

The optimisation involves a complex arrangement of system integration, which includes a SOFC micro-CHP generating heat and electricity, an immersion heater and a thermal storage to recover the maximum possible heat from the SOFC stack. The optimisation is aimed at minimising the use of the immersion heater there by saving energy, cost and CO_2 emissions. Hence an optimisation method is developed to address some of the key questions such us the following: what is the average hot water requirement of the building? What is the base load electricity demand? Is it necessary and is it possible to fully replace existing heat supply technology or can the micro-CHP be adopted to the existing heat supply technology? what operating conditions are the optimal efficiency to maximise the heat recovery from the micro-CHP?

Figure 1. CIBSE headquarters.

Feasibility Study

The feasibility study of the current state of the art SOFC-micro CHP for installation at CIBSE HQ, a Victorian office building was carried out, covering both electrical demand and hot water supply. The office building (figure 1) has 3 kitchens and 7 toilets. As shown on figure 2, the hot water requirement varies throughout the day. Average hot water requirement is 260 L/day. The electrical demand is about 25 kW during office hours and 5kW at night and weekends. A CHP system to match this would produce about 200-300 L of hot water and less than 5 kW of electricity.

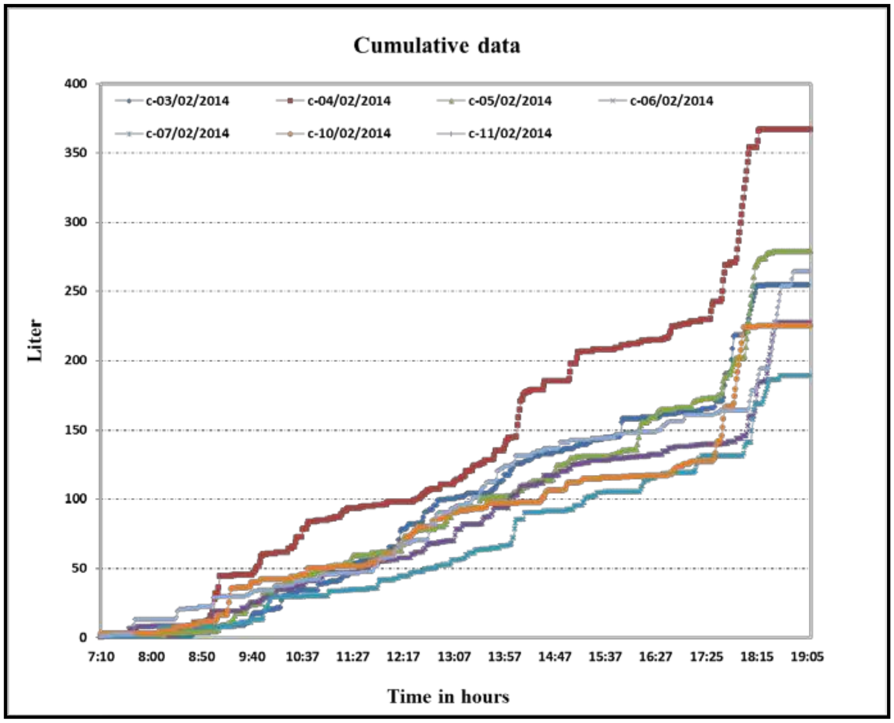

Figure 2.Seven days cumulative data showing hot water requirement throughout the day.

The Installed SOFC Micro-CHP and Heat Recovery System

Heat recovery from fuel cell stack depends on the type of fuel cell. Excess air flow is used to cool high temperature fuel cells such as SOFC. Depending on the design of the system the air flows over the cathode, which is then combusted with unconsumed fuel in an afterburner. The heat recovered from the stack is used to preheat the fuel inlet to the stack. The excess heat is passed through a condensing heat exchanger to provide domestic hot water (DHW) or for space heating. Figure 3 shows the installed BlueGEN SOFC micro-CHP system, manufactured by CFCL Ltd. On the electrical side it is connected so that the building consumes all the power generated by the micro-CHP first with the rest from the grid. On the fuel side it is connected to the standard public natural gas grid. A heat recovery loop extracts heat from the SOFC micro-CHP directly to the connected 300L hot water tank shown in figure 3; the schematic depiction of how the arrangement works is shown on figure 4. To aid the optimization of the heat recovery process the thermal output of the SOFC micro-CHP was monitored by putting a thermocouple in the thermal walls of the heating water loop between the micro-CHP and the hot water tank. Also an electromagnetic flow meter was installed to measure the flow rate of the heating water loop. To ensure maximum benefit from micro-CHP, the system should be controlled correctly, so that when there is a heat demand the micro-CHP would always act as the lead appliance.

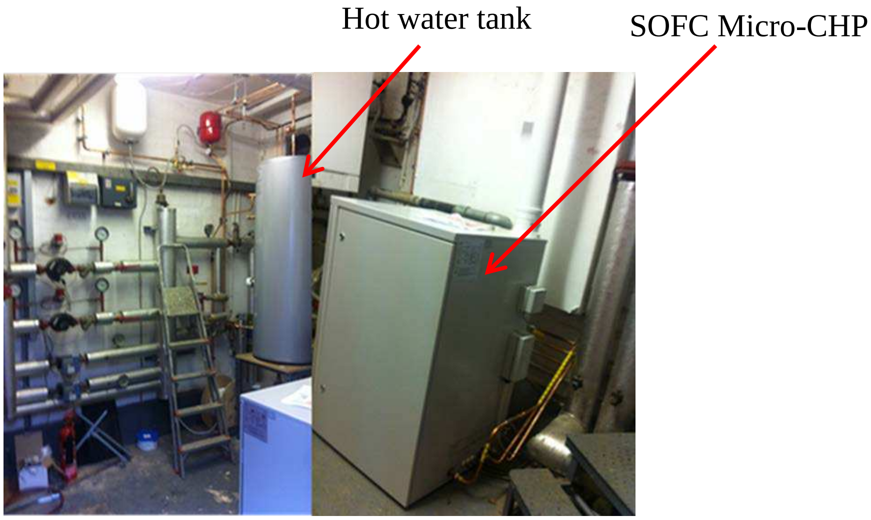

Figure 3. The SOFC micro-CHP unit shown in front is manufactured by Ceramic Fuel Cells Ltd. It is about the size of a washing machine. Also visible is the 300L hot water cylinder.

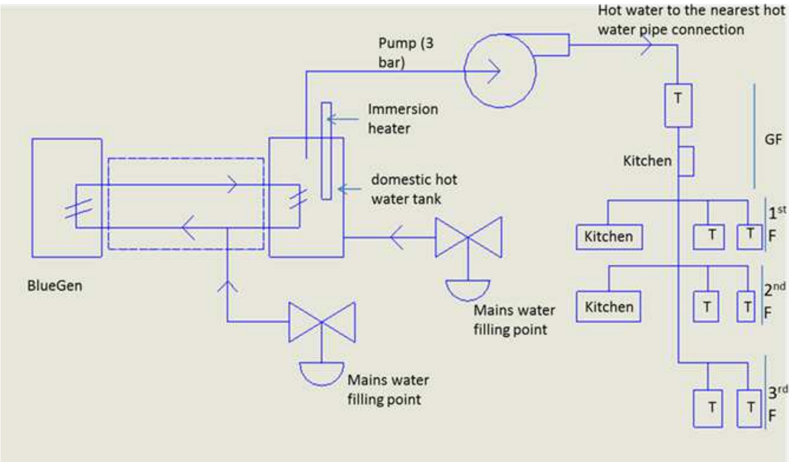

Figure 4. Schematic depiction of fuel cell micro-CHP system arrangement at CIBSE HQ.

Fuel Cell micro-CHP System Test Results

The newly installed SOFC based micro-CHP started generating electricity on the 29th of November 2014. To avoid damage and to reduce stress on the fuel cell stack the power output was not increased above 1.5 kW. The base load electricity demand is 5 kW which means all the power generated by the SOFC micro-CHP is consumed on site. The electrical efficiency data shown in figure 5 shows the system started generating electricity at about 62% efficiency with a fuel input of about 2.5 kW; however, efficiency gradually dropped, stabilising at about 57% indicating slight stack degradation. As can be seen in figure 5, at points A and B the gas supply to the SOFC micro-CHP was interrupted causing a forced shut down. As part of the gas supply systems at CIBSE there is a safety solenoid valve connected after the main Gas Meter, which cuts off the gas supply to the building in the event of power outage. As a result, at point A the SOFC stack was switched off for about 18h during which the temperature dropped by about 200˚C. The stack was reheated and electrical production re-initiated; the SOFC stack recovered well and started generating electricity at 57% efficiency. However about two weeks later the gas supply to the SOFC stack was again interrupted due to power outage at 1am on a Saturday morning. In about three days the stack temperature dropped by about 500˚C. Due to the high temperature drop, it was feared that the stack would not recover to its pre shutdown performance level. To avoid any further damage the stack was nursed back slowly to its operating conditions and generating 1.5 kW electrical output. The SOFC stack maintained similar performance after the second thermal cycling, reaching about 58% efficiency. Since then the stack has been operating at almost 57% efficiency. It appears there is no significant performance drop due to either forced shutdown. However it is not known whether the thermal cycling will affect the long-term efficiency and durability of the stack.

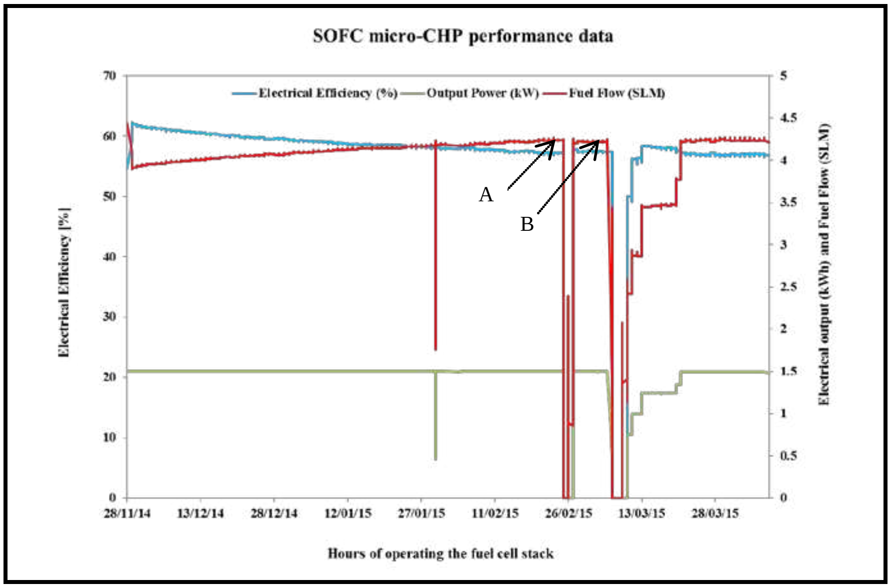

Figure 5. Electrical performance of a newly installed fuel cell stack, initially showing 62% electrical efficiency stabilizing at 57%.

As shown on figure 5, as the efficiency decreases due to degradation the fuel input was increased gradually so as to maintain the 1.5kW power export. As a result after 3506 hours of fuel cell operation, the fuel input was increased from 2.5 kW to 2.8 kW and the electrical efficiency decreased to 57%.

Thermal Performance at 1.5 kW Net Power (AC) Export

The electrical power generation for this SOFC stack is most efficient at 1.5 kW; therefore thermal performance of the fuel cell was tested at 1.5 kW. As the hot water is consumed from the top of the tank, cold water is topped-up at the bottom. As can be seen in figure 2, the hot water demand varies throughout the day, with most of the hot water consumed at about 5:30 pm by the cleaners. At that point the temperature can drop down to about 16˚C. As shown in figure 6, during the weekdays, near the bottom of the tank the hot water tank temperature fluctuates between 35˚C and 45˚C depending on the water usage, a consistent 3 K temperature difference indicating good heat recovery. As shown in figure 7 starting from a return temperature of 15˚C at around 6 pm the SOFC stack requires about 875 minutes to raise the temperature of the hot water tank from about 15˚C to around 45˚C. From this point on, the heat recovery loop temperature difference drops down to about 1.5 K. As shown in figure 6, at the weekend the hot water tank temperature reaches about 60˚C; from this point on, the thermal output of the SOFC stack can only maintain the temperature by compensating the heat losses of the hot water tank and the heat recovery loop.

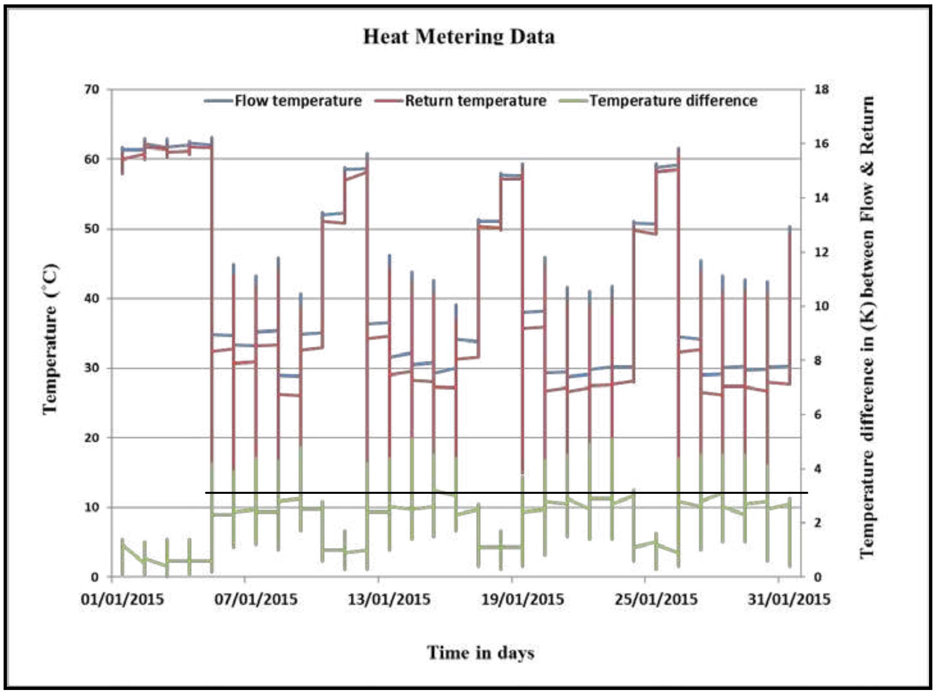

Figure 6. The flow and return temperature, a consistent 3 K difference between Flow and Return temperature shows high heat recovery.

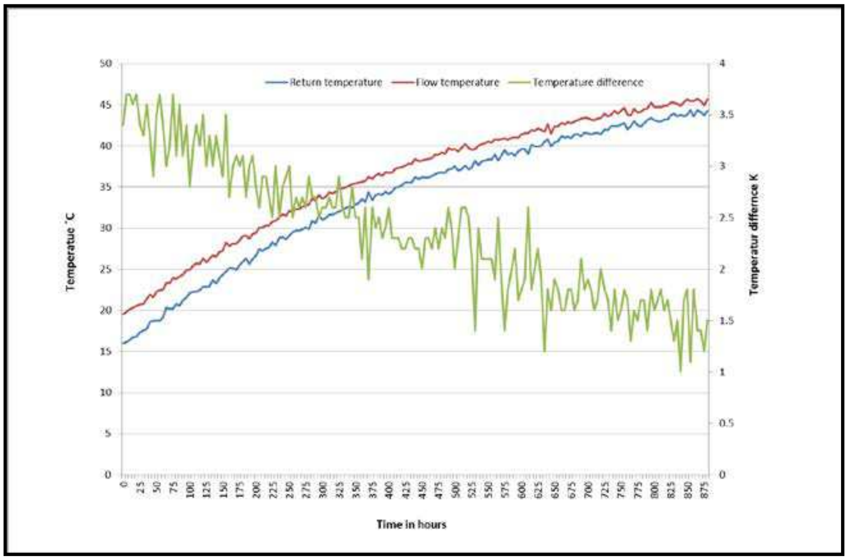

Figure 7. The flow and return temperature showing high heat recovery (3.5 K) when the return temperature is about 15˚ C, and 1.5 K when the return temperature is at 45˚C.

The fuel cell unit generates temperature differences of 3.5 K at the beginning of the loading process, which gradually fall to 1.5 K at the end of the loading process. Figure 8 shows the comparison of the heat output flow temperature and the return flow temperature against the heat recovered in W. The result shows the maximum heat recovered is about 1000 W at the return temperature of 15˚C and 300 W at 45˚C which corresponds to a combined average efficiency of the entire CHP system of about 85%. These results clearly indicate that the lower the temperature of the storage tank the higher the heat recovery. To maximise the heat recovery from the SOFC stack the return temperature should not exceed 45˚C.

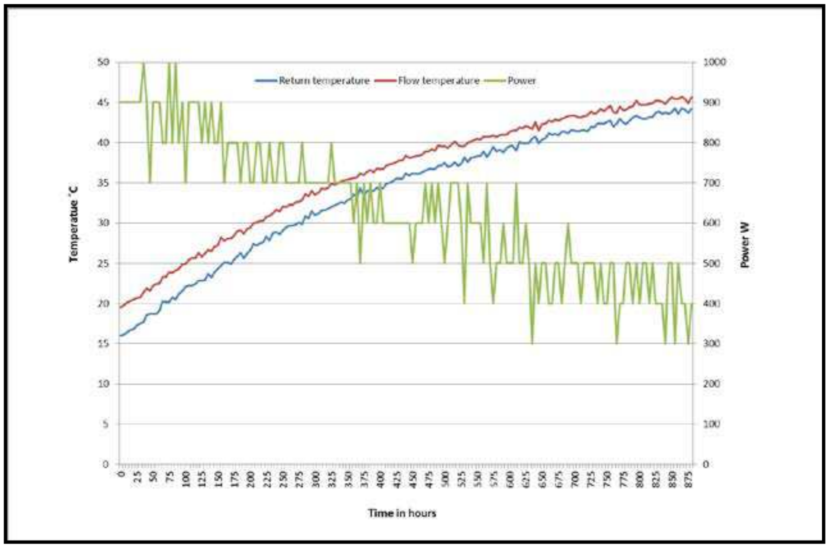

Figure 8. The flow and return temperature showing 1000 W of heat recovered when the return temperature is about 15˚C, and 300 W heat recovered when the return temperature is at 45˚C.

Conclusions

The main objective of this case study was to validate SOFC micro-CHP system compatibility in office buildings and to identify possible performance losses due to degradation of the fuel cell stack. As shown in figure 5, the SOFC based micro-CHP, the BlueGEN, initial performance of 62% drops to about 57% after the first 3506 hours of operation. Although there were two forced shutdowns, the stack recovered well indicating the stack is robust. However it is not known if the forced shutdown will have a long term effect on the durability of the stack. The power production efficiency loss due to stack performance degradation is maintained at 1.5 kW by increasing fuel flow from 2.5 kW to 2.8 kW.

The thermal output of the SOFC micro-CHP depends on the flow return temperature of the heat recovery loop. Results show the maximum heat recovered is about 1000 W at the return temperature of 15˚C and 300 W at 45˚C which corresponds to an average combined efficiency of about 85%. The results clearly indicate that to maximise the heat recovery from the SOFC micro-CHP the return temperature should not exceed 45˚C. The micro-CHP was successfully integrated to the existing heat supply technology. The data shows that heat recovered from the SOFC stack covers most of the domestic hot water requirement. Based on the initial performance, SOFC micro-CHPs could provide significant energy and cost savings when used appropriately in an office type building.

Acknowledgments

CIBSE has invested in a two year research project to produce technical knowledge in fuel cell micro-CHP systems, by looking into the aspects of this new technology's commercial and technological viability and through gaining available information on how to effectively use the systems for building applications. The authors acknowledge the support of CIBSE and InnovateUK through the Knowledge Transfer Partnership (KTP) for funding this research.

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