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Assessment of a novel solid oxide fuel cell tri-generation system for building applications

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Abstract

The paper provides a performance analysis assessment of a novel solid oxide fuel cell (SOFC) liquid desiccant tri-generation system for building applications. The work presented serves to build upon the current literature related to experimental evaluations of SOFC tri-generation systems, particularly in domestic built environment applications. The proposed SOFC liquid desiccant tri-generation system will be the first-of-its-kind. No research activity is reported on the integration of SOFC, or any fuel cell, with liquid desiccant air conditioning in a tri-generation system configuration. The novel tri-generation system is suited to applications that require simultaneous electrical power, heating and dehumidification/cooling. There are several specific benefits to the integration of SOFC and liquid desiccant air conditioning technology, including; very high operational electrical efficiencies even at low system capacities and the ability to utilise low-grade thermal energy in a (useful) cooling process. Furthermore, the novel tri-generation system has the potential to increase thermal energy utilisation and thus the access to the benefits achievable from on-site electrical generation, primarily; reduced emissions and operating costs.

Using empirical SOFC and liquid desiccant component data, an energetic, economic and environmental performance analysis assessment of the novel system is presented.

Significant conclusions from the work include: (1) SOFC and liquid desiccant are a viable technological pairing in the development of an efficient and effective tri-generation system. High tri-generation efficiencies in the range of 68-71% are attainable. (2) The inclusion of liquid desiccant provides an efficiency increase of 9-15% compared to SOFC electrical operation only, demonstrating the potential of the system in building applications that require simultaneous electrical power, heating and/or dehumidification/cooling. (3) Compared to an equivalent base case system, the novel tri-generation system is currently only economically viable with a government's financial support. SOFC capital cost and stack replacement are the largest inhibitors to economic viability. Environmental performance is closely linked to electrical emission factor, and thus performance is heavily country dependent. (4) The economic and environmental feasibility of the novel tri-generation system will improve with predicted SOFC capital cost reductions and the transition to clean hydrogen production.

Keywords: Tri-generation, solid oxide fuel cell, liquid desiccant air conditioning, emission assessment, economic assessment, building application.

1 Introduction

In recent years the dramatic increase in concerns regarding the environmental impact of using fossil fuels, and their accompanying cost, have driven governments, business and consumers towards cleaner energy resources and the use of alternative methods for more efficient energy utilisation. Currently, buildings consume around 40% of the world's primary energy for cooling, heat and power [1]. Most of this energy is from electricity generated at centralised power stations; where at present up to 70% of available energy is wasted. The overall system efficiency is low at 30-40%, leading to a high waste of energy resources, resulting in considerable CO_2 emissions and unnecessarily high running costs. Reducing the energy consumption of buildings can make a substantial contribution towards attaining the EU's 2020, the UK's 2050 and other international carbon emission targets. But this will only be achieved by moving from conventional centralised power generation systems to onsite highly-efficient clean micro-generation technology [2-4].

One of the most promising possibilities for clean micro-generation is solid oxide fuel cell (SOFC) technology, which can generate electricity directly through an electrochemical reaction which brings together hydrogen and oxygen. The only by-products are waste heat, water vapour, and depending on the fuel used a modest amount of CO_2. Chemical to electrical energy conversion efficiencies can be over 50% compared to 30-40% in combustion processes, such as internal combustion engines (ICE) and gas turbines. Technical assessments have demonstrated that if combined heat and power (CHP) technology is used with SOFC, the total system efficiency can be as high as 90% [5, 6]. Liquid desiccant systems are used in heating, ventilation, and air conditioning applications where simultaneous maintenance of temperature and humidity control is an important benefit to the user. This technology is often used in tri-generation system applications where the desiccant system is driven by the heat by-product. If the waste heat from the SOFC is used to drive the liquid desiccant unit, then a tri-generation system will result, supplying not only the power and heat as the conventional CHP technology to the building, but also cooling and humidity control. It has been demonstrated in the literature that the inclusion of liquid desiccant in a tri-generation system configuration can provide significant improvement to total system efficiency [7, 8] and thus greater energy utilisation, providing a range of technical, environmental and economic benefits [3, 4].

The majority of tri-generation systems for building applications reviewed in the literature use the thermal energy rejected by the electrical generator to produce a useful cooling output. The most common technological pairing has been found to be an ICE with a vapour absorption cooling system (VAS) [9-11]. No research publications have been found describing a SOFC or even fuel cell based liquid desiccant tri-generation system. Fuel cells are well suited to tri-generation built environment applications because they produce heat when generating electricity, have high electrical efficiency and excellent load-following characteristics [12]. Moreover, continued technological improvements to fuel cells have, in recent years, increased interest in fuel cell based tri-generation systems [13].

Yu, Han et al. [14] have numerically investigated a tri-generation system incorporating a SOFC and a double-effect water/lithium bromide VAS, high total system efficiencies of 84% or more were reported by the authors, illustrating the benefits of tri-generation systems in applications where heating, cooling and power are required. Margalef and Samuelsen [15] numerically examined a 300kW molten carbonate fuel cell (MCFC) VAS tri-generation system, achieving an overall system efficiency of 72%. The pairing of two off the shelf technologies for tri-generation system construction was shown to be problematic. Margalef and Samuelsen [15] state that the MCFC and VAS chosen for the tri-generation system were close, but not an ideal match. Al-Sulaiman, Dincer et al. [16] presents an energy analysis of a tri-generation plant incorporating a 520kW SOFC, organic Rankine cycle, heat exchanger and single effect VAS. The investigation showed that by incorporating the cooling cycle system efficiency is improved by 22% compared to just having the SOFC and organic Rankine cycle running together. A maximum tri-generation efficiency of 74% has been achieved. Fong and Lee [17] have investigated a SOFC tri-generation system for high-rise buildings in a hot and humid climate. The study focussed on two sizing options. (1) Full SOFC, where the system was sized to peak loads, and (2) partial SOFC, where the system was sized such that peak loads were met by the SOFC and grid, however over the course of one year the system maintains a net zero grid import. The full and the partial SOFC systems generate a 51.4% and 23.9% carbon emission saving respectively, and a 7.1% and 2.8% electricity saving respectively. The full SOFC tri-generation system showed the best environmental and energetic performance due to the partial SOFC systems requirement of grid electricity. However the economics of sizing the tri-generation system to meet peak load capacity was not investigated. Zink, Lu et al. [18] have examined a 110kW SOFC based tri-generation system employing a VAS. Results show that total system efficiency can reach 87% or more and that the combined system shows great advantages both technically and environmentally over other current CHP and tri-generation systems. Darwish [19] has investigated a phosphoric acid fuel cell (PAFC) tri-generation system to meet high air conditioning loads in a large building in Kuwait. The PAFCs thermal (105kW) and electrical outputs (200kW) are used in a VAS and VCS respectively. The system only becomes economically feasible once the fuel cell capital cost drops below 2000\$.kWe^{-1}.

As demonstrated in the literature presented above, tri-generation is a well-known technology for energy conservation in commercial and industrial applications. However, limited work has been completed for tri-generation systems in domestic building applications [20, 21]. Kong, Wang et al. [22] state that the concept of tri-generation systems for individual domestic buildings has only been thought reasonable with the more recent development of heat driven cooling technologies with capacities of <10kW that can operate on low-grade thermal energy (60-90°C). Huangfu, Wu et al. [20] believe the main obstacles to any type of domestic scale tri-generation systems is the high initial cost and complexity of optimum matching of different parts of the system i.e. prime mover and heat driven cooling. Other commonly referenced obstacles include; system size and complexity. However, with recent advances in liquid desiccant based air conditioners for small scale residential applications the development of a fuel cell tri-generation system in domestic homes is possible [23]. Mı́guez [21] and Porteiro [24] state that the introduction of tri-generation systems to the domestic built environment requires the core of the system, the CHP unit, to be compact, cost efficient and easily installed. Pilatowsky, Romero et al. [25] have carried out simulations for a 1kW$_e$ PEMFC coupled to a VAS. Results show that the co-generation process increases total efficiency of the PEMFC system, illustrating the feasibility of using fuel cells in small scale tri-generation system applications. Najafi, Antonellis et al. [26, 27] report on a medium scale (10-20kW$_e$) PEMFC desiccant wheel tri-generation system. The work uses simulations to optimise the system components for building applications. A significant conclusion indicates that positive energy savings can only be achieved if the PEMFC system and it's auxiliary devices performance are appropriately improved. Gigliucci, Petruzzi et al. [28] have conducted extensive work on fuel cell CHP systems in domestic built environment applications, in particular their thermal management. The authors conclude that for the full potential of fuel cell devices operating in built environment applications to be realised, the following aspects need to be considered / resolved: (1) ability of delivering waste heat to a useful heat sink - tri-generation system applications will increase this, and (2) capacity to vary the heat to power ratio / electrical output during operation. Fuel cells with their low heat to power ratios show great promise in terms of total thermal energy utilisation, illustrating why fuel cell technology has been highlighted as a strong candidate for tri-generation domestic built environment applications [12, 23].

To summarise, the literature searches have highlighted a small number of research publications and patents that focus on SOFC tri-generation systems [16, 25, 29-33]. The listed work either focuses on the use of a fuel cell's thermal output in a Rankine bottoming cycle or the use of a VAS. Furthermore, this work is predominately simulation based or aimed at large industrial scale applications. The fuel cell tri-generation systems presented demonstrate good performance in terms of system efficiency, primary energy demand reduction and associated CO_2 emissions / operational costs. However, issues regarding the accurate pairing of prime mover and cooling technologies needs careful consideration to ensure effective system operation. Furthermore, it has been established that the technical and economic viability of any tri-generation system, but particularly fuel cell, presides with the prime mover (fuel cell), not the cooling technology, which is already at a level commensurate with technical and economic practicality.

The work presented in this paper serves to build upon the current literature related to experimental evaluations of SOFC tri-generation systems, particularly in domestic built environment applications. The proposed SOFC liquid desiccant tri-generation system will be the first-of-its-kind. No research activity is reported on the integration of SOFC, or any fuel cell, with liquid desiccant air conditioning in a tri-generation system configuration. The novel tri-generation system is suited to applications that require simultaneous electrical power, heating and dehumidification/cooling. There are several specific benefits to the integration of SOFC and liquid desiccant air conditioning technology, including; very high operational electrical efficiencies even at low system capacities and the ability to utilise low-grade thermal energy in a (useful) cooling process. Furthermore, in many building applications the demand for cooling coincides with a reduction in heating demand. If this heat cannot be fully utilised system efficiency will suffer. The novel tri-generation system has the potential to increase thermal energy utilisation and thus the access to the benefits achievable from on-site electrical generation, primarily; reduced emissions and operating costs. Although no work has been found directly relating to the proposed novel tri-generation system concept, the author’s rationale behind the success of the system is that liquid desiccant air conditioning technology makes better use of low grade thermal energy compared to VAS [34]. Furthermore, liquid desiccant air conditioning regeneration temperatures are lower than that of solid desiccant media [35]. As a result, a SOFC CHP system at the micro to small scale (i.e. <10kW$_e$) with a recovered waste water temperature output of 50-80°C [3, 36] is deemed a well suited technological partnership with liquid desiccant air conditioning technology.

This paper provides a performance analysis assessment of a novel SOFC liquid desiccant tri-generation system for building applications. Using empirical SOFC and liquid desiccant component data, an energetic, economic and environmental performance analysis assessment of a first-of-its-kind system is presented. Specifically, the aim of the paper's performance analysis assessment is to:

1. Validate, empirically, the integration of SOFC and liquid desiccant technology into an efficient and effective tri-generation system.
2. Determine tri-generation system efficiency in a building application.
3. Ascertain whether the proposed tri-generation system is economically and environmentally viable under current conditions compared to an equivalent base case system.
4. Establish the conditions and geographical locations in which the novel tri-generation system is economically and environmentally viable compared to an equivalent base case system.
5. Suggest the future feasibility of the novel tri-generation system with respect to projected changes in global energy resources, conversion techniques and cost.

2 Tri-generation system development

The tri-generation system is comprised of two main components: SOFC and liquid desiccant. The performance of these two system components is documented in sections 2.1 and 2.2 respectively. Following this, section 2.3 presents an energetic performance analysis assessment of the novel tri-generation system.

2.1 Solid oxide fuel cell component

The SOFC used for tri-generation system development and field trial testing in a building application is the BlueGEN CHP unit manufactured by Ceramic Fuel Cells Ltd (CFCL). BlueGEN is a commercially available SOFC CHP system designed for small to medium scale building applications. Operating on natural gas, the unit can be power modulated from 500W$_e$ (25%) to 2kW$_e$ (100%), however it achieves its highest net electrical efficiency of 60% at a 1.5kW$_e$ output. As a result, CFCL have optimised the default operation of the unit at 1.5kW$_e$ to provide the highest electrical efficiency and thus greatest economic benefit to the user. The BlueGEN SOFC unit consists of 51 planar type YSZ (Yttria-stabalised Zirconia) electrolyte layer sets (each layer consist of 4 cells), and operates at 750°C. Hydrogen is produced from natural gas by internal steam reforming (endothermic) on the fuel cell anode, utilising the heat of the electrochemical reaction (exothermic) to create a chemical combined cycle. The BlueGEN SOFC unit is certified for domestic building installations and qualifies for the UK FiT (feed-in-tariff); a tariff paid to the consumer per kWh of generated electricity. The BlueGEN SOFC unit is installed at The University of Nottingham's Creative Energy Homes as shown in Figure 1.

Figure 1 BlueGEN SOFC CHP system installed at The University of Nottingham

The SOFC unit is connected electrically, in parallel, to the national grid in order to export or import power as required. The SOFC unit is connected to the natural gas grid. A waste heat recovery (WHR) circuit delivers the generated heat from the SOFC unit directly to the homes 300L hot water cylinder, which is supplemented by an auxiliary gas boiler. Currently, the BlueGEN's estimate operational lifetime is 15 years; however the unit requires stack replacement every five years. For tri-generation system integration, the liquid desiccant system is installed in-line between the SOFC unit and hot water cylinder, as shown in Figure 2.

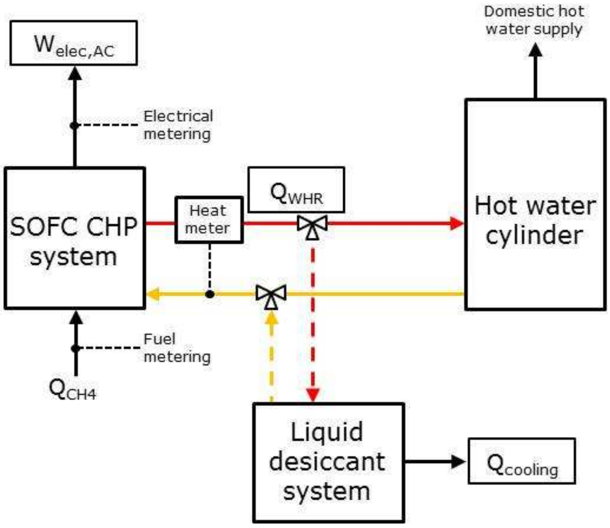

Figure 2 SOFC liquid desiccant tri-generation system schematic

The net AC electrical power output ($\dot{W}_{elec,AC}$) from the SOFC unit is collected using the CFCL online interface. The CFCL interface also records the natural gas fuel input to the SOFC ($\dot{Q}_{CH_4}$). A Diehl Sharky 775 heat meter is used to collect thermal output data from the SOFC. The heat meter measures the water flow rate and supply and return water temperatures in the WHR circuit. Equation 1 is then used to determine the thermal output ($\dot{Q}_{WHR}$).

$$\dot{Q}_{WHR} = \dot{m}_{WHR}\, c_{p,WHR}\left(T_{WHR,flow} - T_{WHR,return}\right) \tag{1}$$

The CHP efficiency (η_{CHP}) is then calculated using Equation 2.

$$\eta_{CHP} = \frac{\dot{W}_{elec,AC} + \dot{Q}_{WHR}}{\dot{Q}_{CH_4}} \tag{2}$$

Figure 3 shows field trial electrical performance data collected from the SOFC unit from 24 March 2014 (point 1) to 12 December 2014 (point 8). This is equivalent to 4865 hours of operation (8 months 18 days). During this period the SOFC unit shows stable operation with an electrical efficiency of 55-60% and availability for power generation of 91.7%. Due to the time taken to heat the stack to 750°C and to avoid thermal cycling, the SOFC unit operates continuously, always aiming to maintain a 1.5kW$_e$ output. As seen in Figure 3 as the stack efficiency degrades over time the fuel input is increased to compensate for this. At an electrical efficiency of 60% the fuel input is 2.5kW. After 4000 hours of operation (point 2 to 5), the stack displayed an electrical efficiency degradation of approximately 6%.

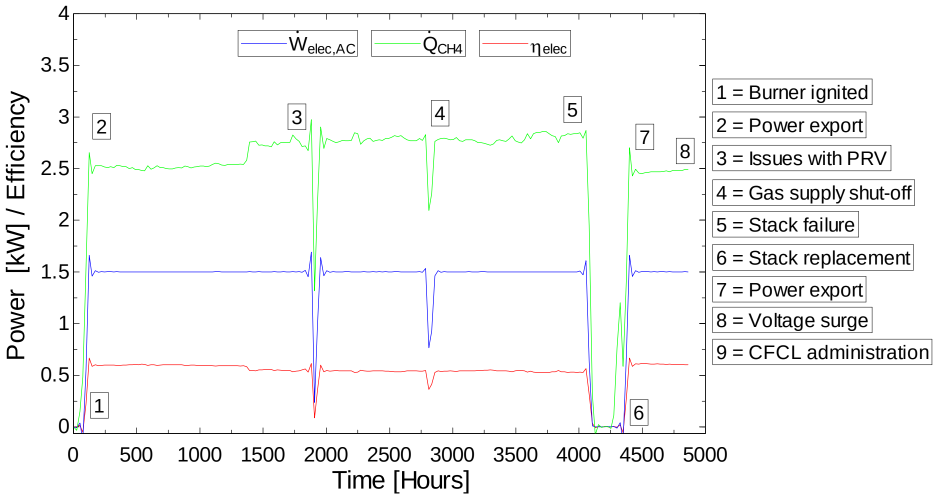

Figure 3 SOFC field trial electrical performance data

Figure 4 presents electrical and thermal performance characterisation of the SOFC CHP system in a building application using data from [37] and [38]. During the performance characterisation, a 2L.min^{-1} water volumetric flow in the WHR circuit has been used. This is equal to the value used in the liquid desiccant performance assessment in [39] and thus tri-generation system integration is a rational concept. From Figure 4a it is evident that the net electrical efficiency increases as the electrical capacity increases, from 14% at 200We up to a maximum of 60% at 1500We, it then decreases to approximately 56% at a 2000W_e capacity. The thermal output from the SOFC increases fairly linearly from 320W_{th} at 200We up to 540W_{th} at 1500kW_e. The thermal output increase is then much steeper, up to a maximum of 1000W_{th} at 2000W_e. At the optimised 1500We output a CHP efficiency of 81.6% is achieved.

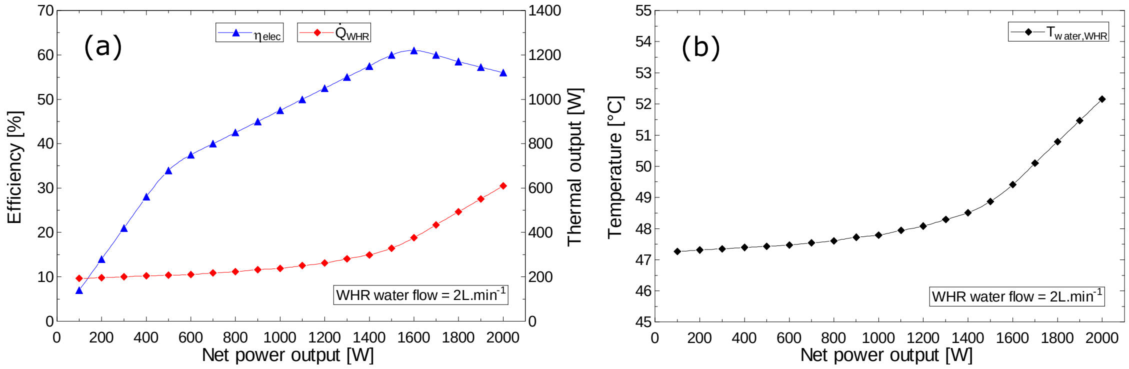

Figure 4 (a) SOFC electrical efficiency and thermal output [38], and (b) WHR flow water temperature as a function of electrical output

Figure 4b shows the flow water temperature in the SOFC WHR loop as a function of electrical power output. The flow water temperature is calculated based on the thermal output data presented in Figure 4a, a 2L.min^{-1} water volumetric flow and a 45°C return water temperature in the WHR circuit. The flow water temperature ranges between 47°C at 100We output up to a maximum of 52°C at a 2000W$_e$ output. As demonstrated in [39] this is sufficient for effective desiccant solution regeneration. Due to limited variation in the SOFC CHP system's operation and thus outputs it is primarily the operation of the desiccant system that is optimised to facilitate successful tri-generation system integration [39].

With reference to Figure 3, there have been three key events in the lifetime of the SOFC unit, (1) an unforeseen gas shut-off (point 4) causing stack cool down and thermal contraction, leading to an electrical efficiency drop, and eventual stack failure (point 5) and replacement (point 6), (2) A 415 volt voltage surge at The Creative Energy Homes causing irrevocable damage to the power electronics and thus stack cool-down, again leading to the requirement of power electronic and stack replacement (point 8). (3) CFCL going into administration, and thus not being able to carry-out the required repair works post voltage surge. At the time of writing the SOFC unit is not operational.

2.2 Liquid desiccant component

A liquid desiccant air conditioning system developed by the authors specifically for tri-generation/waste heat driven system applications, in particular with SOFC technology, has been previously documented in detail in [39]. The desiccant system uses a semi-permeable micro porous membrane based cross flow contactor, operating with a low cost, environmentally friendly, non-corrosive potassium formate ($CHKO_2$) desiccant solution. The merits and operational considerations of employing a potassium formate desiccant solution over other commonly used liquid desiccants such as lithium chloride or calcium chloride are provided in a previous work [36]. Figure 5a provides a schematic diagram of the complete liquid desiccant system with labelled components and Figure 5b shows a photograph.

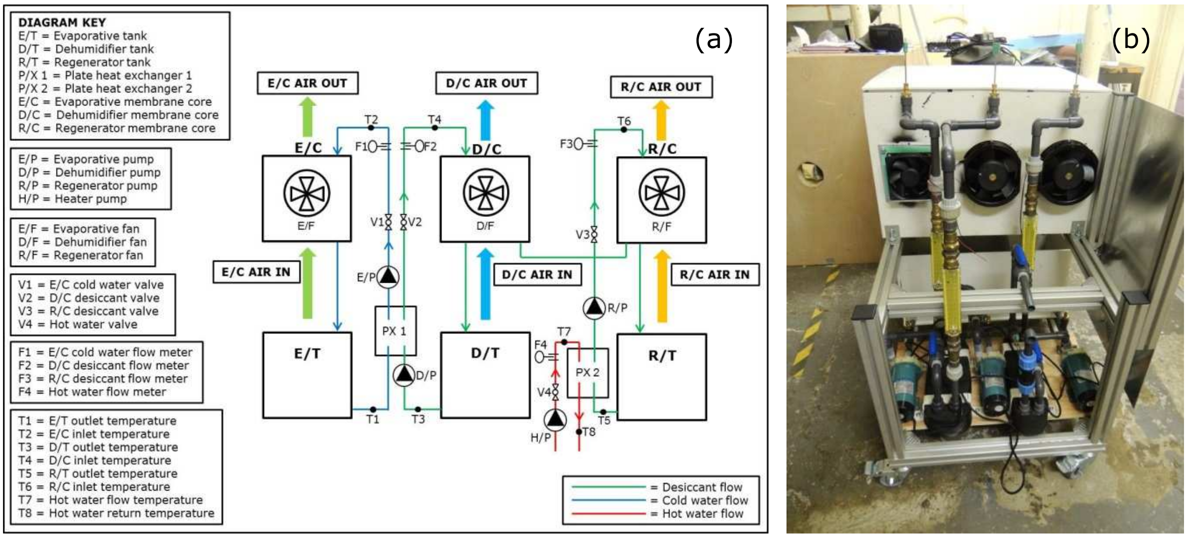

Figure 5 Liquid desiccant system (a) schematic with labelled components, and (b) photograph

The paper assesses in detail the impact inlet environmental conditions (air temperature and relative humidity) and operational conditions (desiccant solution volumetric, water flow temperature and hot water volumetric flow in the heating circuit) have on liquid desiccant system performance. Refer to [39] for a detailed description of the liquid desiccant system's experimental set-up, experimental method and full results/analysis.

The main metric used to evaluate the performance of the liquid desiccant system is thermal COP (COP_{th}) as shown in Equation 3. Where, $\dot{Q}_{cooling}$ is the dehumidifier cooling output and $\dot{Q}_{reg}$ is the regenerator thermal input.

$$\mathrm{COP}_{th} = \frac{\dot{Q}_{cooling}}{\dot{Q}_{reg}} \quad \mathbf{3}$$

In order for the desiccant air conditioning system to operate continuously, the mass of vapour absorbed by the desiccant solution in the dehumidifier must be removed in the regenerator. Adequate regenerator thermal input is therefore required.

Figure 6 shows the variation in liquid desiccant system performance with dehumidifier desiccant solution volumetric flow. The assessment has been performed at a set desiccant system inlet air condition of 30°C and 70% relative humidity. Figure 6a shows the hot water volumetric flow in the heating circuit needs to be increased as the dehumidifier desiccant solution volumetric flow is increased. At a desiccant flow of 1.5L.min^{-1} the hot water volumetric flow is 2.17L.min^{-1}. As desiccant volumetric flow increases to 2.5L.min^{-1} the hot water volumetric flow needs to be increased to 2.353L.min^{-1} and at a desiccant volumetric flow of 3.5L.min^{-1} the hot water volumetric flow needs to be increased to 2.802L.min^{-1}. At a set hot water volumetric flow of 2L.min^{-1} Figure 6b shows that the hot water flow temperature needs to be increased as the dehumidifier desiccant solution volumetric flow is increased, from 48°C at 1.5L.min^{-1}, 50.27°C at 2.5L.min^{-1} and to 53.3°C at 3.5L.min^{-1}. At a set inlet dehumidifier desiccant solution volumetric flow of 3.5L.min^{-1}, the COP_{th} values seen in Figure 6a and Figure 6b are 0.52 and 0.66 respectively. Over the dehumidifier desiccant solution volumetric flow range investigated, the electrical COP (COP_{el}) varies between 5.7 and 7.1.

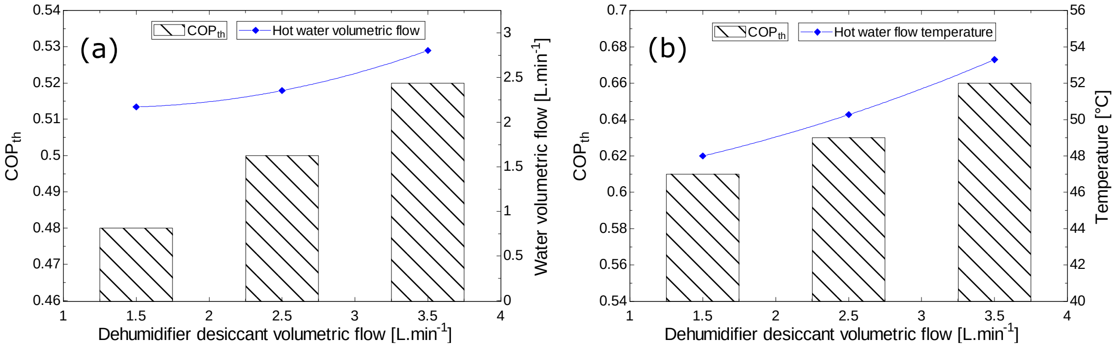

Figure 6 Liquid desiccant system performance with dehumidifier desiccant solution volumetric flow

The experimental evaluation in [39] validates the concept of integrating SOFC and liquid desiccant air conditioning technology into an efficient and effective tri-generation system. This is primarily due to good dehumidification capacity and effective regeneration of the potassium formate solution at a 0.65-0.7 solution mass concentration. Encouraging COP_{th} values in the range of 0.4-0.66 have been demonstrated when operating with a low grade thermal input (45-60°C) typical of a SOFC CHP system of the studied scale.

2.3 Energetic performance analysis assessment

Due to the SOFC's operational issues it was not available for tri-generation system integration. As a result, the paper uses empirical SOFC component data presented in section 2.1 and liquid desiccant component data presented in section 2.2 and [39] to perform a theoretical integration analysis of the novel system. Although the paper uses empirical SOFC and liquid desiccant component data to perform the theoretical integration analysis, the technical feasibility of tri-generation system integration is practical. This is because both the SOFC thermal output and liquid descant thermal input are both considered low-temperature (40 - 60°C) and operate at atmospheric pressure. Furthermore, in a domestic building context, the SOFC and liquid desiccant components can be connected using standard heating system copper/plastic pipe. Similarly, typical domestic heating system three port solenoid valves control the flow of thermal energy between the SOFC component and domestic hot water / liquid desiccant regeneration requirements.

Using empirical WHR flow water temperature from the SOFC CHP system, shown in Figure 4b, and empirical liquid desiccant component data from [39], the COP_{th} and resulting cooling output of the liquid desiccant system, operating with the SOFC CHP system's thermal output, is determined. Using these data tri-generation system efficiency (η_{tri}) is calculated. Tri-generation system efficiency is defined in Equation 4 as the ratio of the overall tri-generation system energy conversion (electricity and heating and/or cooling) over the total amount of energy input to the system.

$$\eta_{tri} = \frac{\dot{W}_{elec,AC} + \dot{Q}_{WHR,net} + \dot{Q}_{cooling}}{\dot{Q}_{CH_4}} \qquad \textbf{4}$$

Table 1 presents the results from the integration of the SOFC and liquid desiccant components into a complete tri-generation system at a net 1.5kW$_e$ and 2kW$_e$ output, with a desiccant system inlet air condition of 30°C and 70% relative humidity. In order to obtain balanced desiccant system operation, the desiccant solution volumetric flow in the dehumidifier and regenerator (shown in Table 1) has been adjusted according to the thermal output available from the SOFC. The parasitic energy consumption (110W) of the liquid desiccant system has been included in the evaluation.

Table 1 Tri-generation system energetic performance

Variable	**$1.5kW_e$**	**$2kW_e$**
η_{elec} (%)	60	56
$\dot{Q}_{CH_4}(W)$	2500	3571
$\dot{Q}_{WHR}(W)$	540	1000
$T_{WHR,flow}(°C)$	48.87	52.16
η_{CHP} (%)	81.6	84
Desiccant volume ($L.min^{-1}$)	1.74	3.16
COP_{th}	0.614	0.649
$\dot{Q}_{cooling}(W)$	332	649
Dehumidifier *MRR* ($g.s^{-1}$)	0.2515	0.2941
η_{tri} (%)	68.9	71.1
Δ% PED (CHP/TRI)	51.41 / 46.98	50.21 / 46.79
Δ% Cost (CHP/TRI)	62.84 / 60.67	61.53 / 60.53
Δ% Emissions (CHP/TRI)	51.21 / 68.96	50.01 / 68.26

Electrical import cost and emission factor = 0.172£.kWh^{-1} [40] and 0.555kgCO_2.kWh^{-1} [41] / Natural gas import cost and emission factor = 0.0421 £.kWh^{-1} and 0.184kg CO_2.kWh^{-1} [42]

The system integration, based on empirical data, demonstrates high tri-generation system efficiency in the range of 68-71% is attainable when combining SOFC and liquid desiccant air conditioning technology. The SOFC unit has a low heat to power ratio, particularly at the $1.5kW_e$ condition, this is because it is an electrically optimised device (fuel utilisation of ~85%). As a result, there is limited thermal output available for desiccant solution regeneration. However, the liquid desiccant system, operating with a potassium formate solution at a 0.65–0.7 solution mass concentration, has a low regeneration temperature requirement, and thus makes good use of the low-grade heat output from the SOFC to generate a meaningful quantity of dehumidification/cooling. At the 2kW$_e$ condition, electrical efficiency is lower, but the thermal efficiency is higher. As a result, almost 650W of cooling is produced. The inclusion of liquid desiccant air conditioning technology provides an efficiency increase of 9-15% compared to SOFC electrical operation only, demonstrating the potential of the system in building applications that require simultaneous electrical power, heating and/or dehumidification/cooling. The performance of the novel tri-generation system is competitive with other systems of this capacity reported in the literature [7, 9, 22, 43].

Table 1 shows that CHP and tri-generation efficiency is highest for the 2kW$_e$ case. However the primary energy demand (PED), cost and emission savings, compared to an equivalent base case system are highest for the 1.5kW$_e$ case. The base case system is defined as a conventional separate system, comprising grid electricity, natural gas fired boiler and electrically driven vapour compression system (VCS). The capacities of the base case system components are assumed equal to the respective electrical (1.5kW$_e$ / 2.0kW$_e$), heating and cooling capacities of the tri-generation system employed in the comparison. The electrical efficiency of the base case system has been assumed as 33%, a figure considering the efficiency of utility scale electrical generation plus transmission losses [9]. The thermal efficiency of the gas fired boiler has been assumed as 90%. The electrical coefficient of performance (COP_{el}) of the VCS is assumed constant at 2 [44]. Thus, the overall efficiency of the base case system can be calculated for any given electrical, heat and cooling output from the SOFC CHP / tri-generation system. Table 1 lists the associated cost and emission factors of grid electricity and natural gas used in the assessment. These are typical of the UK. Because electricity has a higher associated cost and emission compared to natural gas, greater savings are made for the 1.5kW$_e$ case due to the higher electrical efficiency. In tri-generation cooling mode, relative cost and emission reductions compared to the base case system for the 1.5kW$_e$ and 2kW$_e$ cases are around 60% and

70% respectively, demonstrating the potential of a first-of-its-kind SOFC liquid desiccant tri-generation system for building applications.

Section 2 has validated, empirically, the integration of SOFC and liquid desiccant technology into an efficient and effective tri-generation system. The energetic performance analysis demonstrates high tri-generation system efficiency is attainable at low system capacities. The encouraging performance is primarily due to the high electrical efficiency of the SOFC and the reasonable COP_{th} of the liquid desiccant system when operating on low grade waste heat. The operational issues encountered with the SOFC illustrate the real challenge of fuel cell deployment in the built environment. Reliability, durability and cost currently pose a great barrier to fuel cell's wider use. Not until these issues are addressed will the operational advantages of fuel cells operating in the built environment be fully realised.

3 Emission and economic performance analysis assessment

The aim of this section is to conduct a detailed economic and emission performance analysis assessment of the novel SOFC liquid desiccant tri-generation system. This is to determine whether it is a viable alternative to other comparable systems. The assessment uses the SOFC tri-generation system performance data presented in Table 1 operating at a 1.5kW$_e$ and 2.0kW$_e$ capacity, and compares it to an equivalent base case system comprising grid electricity, natural gas fired boiler and electrically driven VCS. As in the energetic analysis, presented in section 2.3, the capacities of the base case system components are assumed equal to the respective electrical (1.5kW$_e$ / 2.0kW$_e$), heating and cooling capacities of the tri-generation system employed in the comparison. The electrical efficiency of the base case system has been assumed as 33%, thermal efficiency of the gas fired boiler has been assumed as 90% and the COP$_{el}$ of the VCS is assumed constant at 2.

3.1 Economic assessment

In this section, an economic assessment of the novel SOFC liquid desiccant tri-generation system operating within a UK and worldwide economic climate is presented. The economic assessment compares the 1.5kW$_e$ and 2.0kW$_e$ capacity tri-generation systems to an equivalent base case system over a 15 year time period. The economic evaluation metrics used are: net present cost (NPC), equivalent uniform annual cost (EUAC) and simple pay-back period (SPBP). The unit cost of electricity, unit cost of natural gas and the capital cost of the SOFC are varied, in a reasonable range, to carry out a sensitivity analysis of the NPC and SPBP. Using electrical unit cost data published by the International Energy Agency [45], the economic performance of the tri-generation system in the context of different countries is presented.

3.1.1 Economic assessment metrics

NPC, EUAC and SPBP are used to assess the economic performance of the novel SOFC liquid desiccant tri-generation system compared to a base case system.

3.1.1.1 Net present cost (NPC)

Net present value (NPV) is an economic tool used to equate the total cost of a project over a specified time period to the total cost today, taking in to account the time value of money. NPV is a good indicator of how much value an investment or project brings to an investor, and is widely used in economic engineering to assess feasibility. However, there are many kinds of systems or projects, such as the SOFC tri-generation system, where there are no sales or incomes. In this case it is common to use net present cost (NPC). Equation 5 is used to calculate NPC [23].

$$\mathrm{NPC} = \sum_{t=0}^{N} \frac{AA_{TC}}{(1+i_r)^n} + I_{cc} \tag{5}$$

AA_{TC} is the adjusted annual total costs (£), i_r is the interest rate, n is the year number and I_{cc} is the initial capital cost (£). Selection of a suitable interest/discount rate is based upon risk, opportunity cost or an alternative investment. In engineering based analysis 7% is a widely used value [23]. If inflation is being considered, the adjusted annual total cost (AA_{TC}) is calculated using Equation 6.

$$AA_{TC} = A_{TC}\left(1+i_f\right)^n \tag{6}$$

A_{TC} is the non-adjusted annual total costs (£), i_f is the inflation rate and n is the year number. The scrap value (SV) of the system at the end of the project's life should be considered, and subtracted from the final expenditure. In NPC analysis the annual total expenditure or costs (AA_{TC}) are given as positive figures, and thus the NPC at the end of a system lifetime will be positive. When two or more systems are being evaluated over the same time period, the system with the lowest NPC should be selected.

3.1.1.2 Equivalent uniform annual cost (EUAC)

The equivalent uniform annual cost (EUAC) is the annual cost of the project or system equivalent to the discounted total cost or NPC. EUAC is calculated by multiplying the NPC by the capital recovery factor (CRF) as shown in Equation 7.

$$\mathrm{EUAC} = \mathrm{NPC}\left[\frac{i_r(1+i_r)^n}{(1+i_r)^n - 1}\right] \tag{7}$$

3.1.1.3 Simple pay-back period (SPBP)

The simple pay-back period (SPBP), shown in Equation 8, is used to determine the time required to recoup the funds expended in an investment, or to reach the break-even point. Generally, in engineering projects investors consider a SPBP of five years as acceptable. The SPBP does not account for the time value of money; however it is a useful tool for the quick assessment of whether a project or system is a viable option.

$$\mathrm{SPBP} = \frac{I_{cc}}{\text{Annual savings}} \tag{8}$$

I_{cc} is the is the initial capital cost of the system (£). Annual savings are calculated by subtracting the annual total cost (A_{TC}) of the base case system from the annual total cost of the proposed system.

Table 2 lists the constants used for the economic assessment of the novel tri-generation and equivalent base case system. Where relevant, these constants are adopted in the environmental assessment in section 3.2.

Table 2 Economic and environmental assessment constants

Constant	Value	Ref
System lifetime (N)	15 years	[46]
SOFC CHP system cost & installation	£20,950	[4]
Liquid desiccant system cost	£2700	
Potassium formate solution cost (20kg)	£235	
SOFC stack replacement cost and system maintenance	£5000 / 5 years	
UK micro-CHP feed-in-tariff (FiT)	0.125 £.kWh^{-1}	[47]
Boiler and installation cost	£1300	
VCS capital cost	£500 / kW cooling	[48]
Annual VCS maintenance cost	10% of VCS capital cost	
Annual gas check	£60	
Average natural gas unit cost	0.0421 £.kWh^{-1}	[42]
Average electricity unit cost	0.172 £.kWh^{-1}	[40]
Average yearly VCS COP$_{el}$	2	[44]
Average heating system efficiency (boiler + distribution)	85.5%	
Annual cooling time required	1200hr.yr^{-1}	[23]
Interest rate (i_r)	7% (constant)	
Inflation rate (i_f)	3% (constant)	
Scrap value (SV)	10% of capital cost	[23]

In the UK, fuel cell CHP of 2.0kW$_e$ or less qualifies for the micro-generation FiT [47]. Under this scheme, the UK government pays 0.125£.kWh^{-1} of electricity generated, regardless of whether it is consumed or exported. Where relevant, the economic assessment considers the FiT.

3.1.2 Economic assessment results

Figure 7a and Figure 7b show the respective NPC of the 1.5kW$_e$ and 2.0kW$_e$ tri-generation systems and equivalent base case systems over a 15 year period. The assessment considers the performance of the tri-generation system with and without FiT support. The initial NPC in year 0 is the system investment cost, which is much higher for the tri-generation system compared to the base case. The NPC of the systems increases over time due to the annual operating costs. The tri-generation system with FiT support displays only a marginal increase in the NPC over the 15 year period because the FiT almost pays for the annual operating cost of the system. For the tri-generation systems, an NPC spike is seen at year five and ten; this is due to the stack replacement requirement. The small dip in NPC at year 15 is due to the scrap value of the systems.

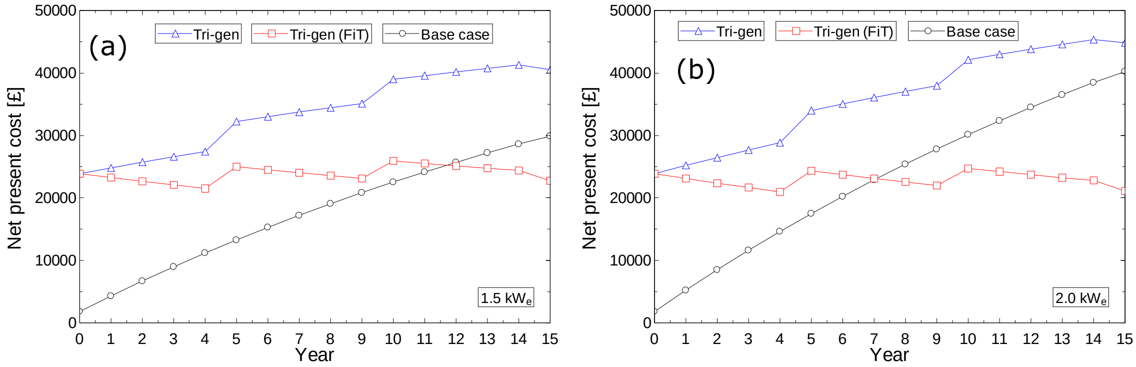

Figure 7 NPC comparison at a 1.5kW$_e$ in (a) and 2.0kW$_e$ in (b) capacity between the tri-generation system with and without the FiT and the base case system

Table 3 presents the NPC, EUAC and SPBP results for the tri-generation and base case systems.

Table 3 Economic assessment results

	1.5kW$_e$ tri	**1.5kW$_e$ base**	**2.0kW$_e$ tri**	**2.0kW$_e$ base**
NPC (no FiT)	£40544	£29898	£44818	£40257
NPC (FiT)	£22770	---	£21120	---
EUAC (no FiT)	£4451	£3283	£4921	£4420
EUAC (FiT)	£2500	---	£2319	--
SPBP (no FiT)	19.8 years	---	14.7 years	---
SPBP (FiT)	9.8 years	---	7.3 years	--

Without FiT support, the NPC of both the 1.5kW$_e$ and 2.0kW$_e$ tri-generation systems are 26% and 10% higher than the equivalent base case systems respectively. However, with FiT support there is a 31% and 90% reduction in the NPC of the 1.5kW$_e$ and 2.0kW$_e$ tri-generation systems compared to the equivalent base case systems respectively. When the FiT is considered the annual revenue means the tri-generation systems have a favourable NPC compared to the base case in year 11.5 for the 1.5kW$_e$ tri-generation system and year 7 for the 2.0kW$_e$ tri-generation system. The NPC of the 1.5kW$_e$ tri-generation system is lower than the 2.0kW$_e$ tri-generation system when no FiT is considered, but higher when the FiT is considered. The higher NPC seen in the 2.0kW$_e$ tri-generation system without FiT is due to the higher fuel input requirement, and thus higher annual operating costs. However, when FiT is considered the 2.0kW$_e$ tri-generation system provides greater annual revenues and thus a lower NPC. Both with and without FiT support, the 2.0kW$_e$ tri-generation system has a lower SPBP compared to the 1.5kW$_e$ tri-generation system. Although the 2.0kW$_e$ tri-generation system suffers an electrical efficiency reduction and thus a greater fuel input, the higher electrical capacity means it is offsetting more grid derived electricity. Per kWh, grid derived electricity has a higher associated cost compared to natural gas, and thus the SPBP of the 2.0kW$_e$ tri-generation system is lower. Furthermore, the 2.0kW$_e$ tri-generation system has a greater cooling output, and thus the equivalent base case system requires more grid derived electricity for the VCS. In all cases the tri-generation systems generate annual operating cost savings compared to the base case systems. The high NPC and SPBP of the tri-generation systems are therefore due to the capital cost of the SOFC.

Figure 8a compares the economic performance of the 1.5kW$_e$ tri-generation system and equivalent base case system with respect to the unit cost of electricity. No FiT is considered. The unit cost of electricity does not affect the NPC of the tri-generation system, only the base case system. As the unit cost of electricity increases from 0.05 to 0.6£.kWh^{-1} the NPC of the base case system increases, and thus the economic feasibility of the tri-generation system improves. At an electrical unit cost of 0.2458£.kWh^{-1} there is a NPC break-even point between the tri-generation and base case system. Above 0.2458£.kWh^{-1} the 1.5kW$_e$ tri-generation system has a better (lower) NPC and should be considered over the base case system. At an electrical unit cost of 0.2458£.kWh^{-1} the tri-generation system has a SPBP of 12 years. For the SPBP to fall below five years, an electrical unit cost of 0.55£.kWh^{-1} is required. In comparison, the 2.0kW$_e$ tri-generation system has a NPC break-even electrical unit cost of 0.1955£.kWh^{-1}. Due to the continual rise in utility electricity prices, the break-even electrical unit cost which produces tri-generation system economic feasibility are realistic and not far off current prices as demonstrated in Figure 9.

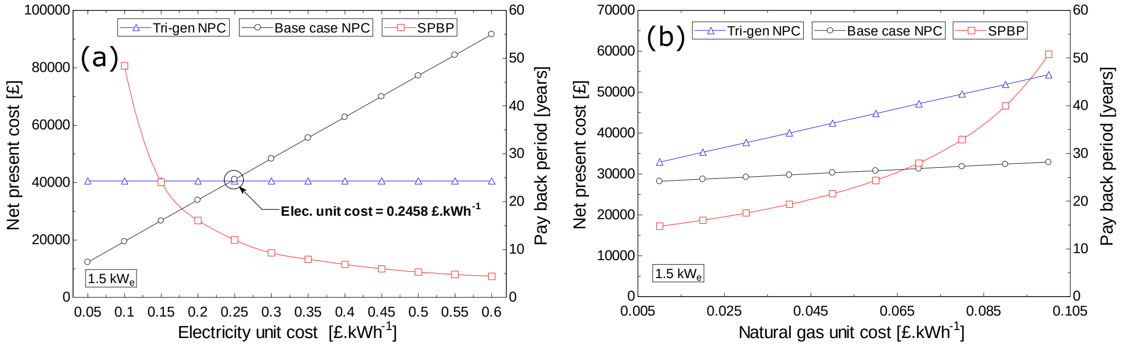

Figure 8 NPC and SPBP comparison between the 1.5kW$_e$ tri-generation system and base case system with (a) electricity unit cost, and (b) natural gas unit cost

Figure 8b compares the economic performance of the 1.5kW$_e$ tri-generation system and equivalent base case system with respect to the unit cost of natural gas. No FiT is considered. Natural gas unit cost affects both the tri-generation and base case system's NPC. As the unit cost of natural gas increases from 0.01 to 0.1£.kWh^{-1} the NPC of both the tri-generation and base case systems increase. The tri-generation system is more sensitive to changes in the unit cost of natural gas compared to the base case system due to a greater proportionate demand. For the 1.5kW$_e$ tri-generation system there is not a natural gas unit cost that makes the tri-generation system favourable i.e. a NPC break-even point. As the natural gas unit price is increased the reduction in NPC between the base case and tri-generation system increases, and as a result the SPBP increases. As the natural gas unit cost is increased from 0.01£.kWh^{-1} to 0.1£.kWh^{-1} the tri-generation system SPBP increases from 14 years to 51 years. The 2.0kW$_e$ tri-generation system does have a NPC break-even natural gas unit cost of 0.0233£.kWh^{-1}. However this is very low and not realistic in the current economic climate where fossil fuels have such value.

Figure 9 shows the NPC of a 1.5kW$_e$ and 2.0kW$_e$ equivalent base case system in a range of different counties with respect to electrical unit cost data published by the International Energy Agency [45]. The NPC of the respective tri-generation systems (horizontal lines) are plotted to indicate which countries the novel system is currently economically viable in. Based on the current assumptions, the novel tri-generation system (1.5kW$_e$ and

2.0kW$_e$) is only economically viable in Denmark where the unit cost of electricity is 0.262£.kWh^{-1}. The largest different between the NPC of the tri-generation and base case system is in China, where the unit cost of electricity is as low as 0.0512£.kWh^{-1}. Based purely on economic performance, the novel tri-generation system is more suited to European locations, where on average the unit cost of electricity is higher than Asia and the Americas. As discussed in Figure 8a, the 2.0kW$_e$ tri-generation system has a lower NPC break-even electrical unit cost. As a result, the 2.0kW$_e$ system is almost feasible in the current Australian economic climate. Section 3.2 assesses the environmental performance of the tri-generation system in the same countries. The aim is to highlight any geographical similarities or differences between the economic and environmental feasibility of the novel system.

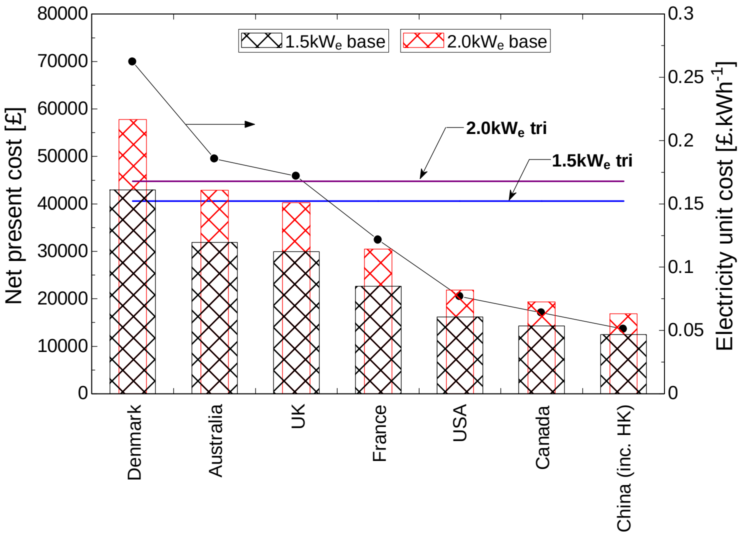

Figure 9 NPC comparison between the 1.5kW$_e$ and 2.0kW$_e$ tri-generation system and base case system with respect to country of operation

Figure 10a shows the NPC of the 1.5kW$_e$ tri-generation system and equivalent base case system with respect to the SOFC capital cost. The capital cost of the tri-generation system, operating at a 1.5kW$_e$ capacity, needs to be £9715 or less for it to be economically viable compared to the base case system. At a 2.0kW$_e$ capacity the required SOFC capital cost is £16135. As the capital cost of the SOFC increases, the SPBP increases. At the 1.5kW$_e$ NPC break-even point of £9715 the SPBP is 12.8 years. Although not shown in Figure 10a, variation in the liquid desiccant system capital cost has a negligible impact on NPC and SPBP. Reducing the liquid desiccant system capital cost by 50% results in a 4.5% reduction in the SPBP. Reducing the SOFC capital cost by 50% results in a 32% reduction in the SPBP, demonstrating that tri-generation system economic viability presides with reducing the capital cost of the SOFC.

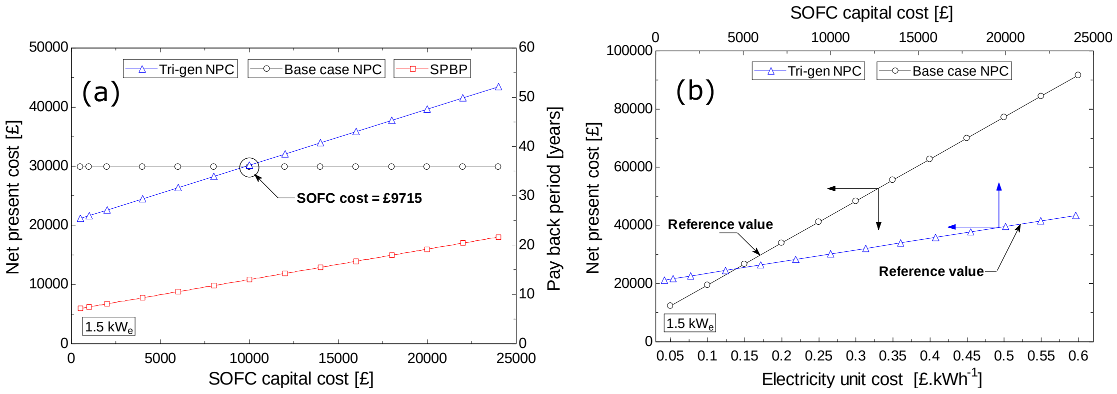

Figure 10 NPC and SPBP comparison between the 1.5kW$_e$ tri-generation system and base case system with (a) SOFC capital cost, and (b) electricity unit cost and SOFC capital cost

Figure 10b shows the NPC for the 1.5kW$_e$ tri-generation and equivalent base case system with respect to SOFC capital cost and unit cost of electricity respectively. Up to an electricity unit cost of 0.11£.kWh^{-1} the base case system is always better than the tri-generation system. However at the electrical unit cost reference value of 0.172£.kWh^{-1}, the 1.5kW$_e$ tri-generation system is competitive when the SOFC capital cost is less than £9500. At the intersection point, the tri-generation system is economically favourable if the SOFC capital cost is less than £4750 with an electrical unit cost of greater than 0.14£.kWh^{-1} (i.e. UK, Australia).

3.1.3 Economic assessment conclusions

Within a UK economic climate it has been demonstrated that the NPC of the novel tri-generation system is only favourable when FiT is considered, in which case the 2.0kW$_e$ output is best. The tri-generation system has a lower annual operating cost than the base case; however, NPC and SPBP analysis demonstrates that the novel system is currently uneconomical. This is primarily due to the SOFC capital cost and the requirement of stack replacement, not the liquid desiccant unit capital cost. In the current UK economic climate the SOFC capital cost needs to be less than £9000 for the tri-generation system to be competitive. This is a cost estimate supported by Staffell and Green [49] in their economic evaluations of SOFC CHP systems. PEMFC technology has demonstrated considerable price reduction over the last six years. The 1kW$_e$ Panasonic unit had a unit cost of £27,300 in 2009, but as of 2015 it is being supplied to energy companies for £3600. CFCL forecast that they can supply the BlueGEN SOFC unit for £5200 once in mass production. Currently, the much lower PEMFC unit costs are due to the technology being around five years ahead of SOFC [4]. Many commercial developers believe the future of cheaper fuel cell technology lies with SOFC systems as they do not need to use expensive platinum catalysts like PEMFC. Based on the example of PEMFC cost reductions, significant SOFC cost reductions can be anticipated. The SOFC cost target figures presented are therefore sensible and could be realistically achieved in the next five to ten years, making the tri-generation system economically viable in almost all cases.

Currently, the tri-generation system becomes competitive, and even demonstrates good profitability, compared to the base case system when a government’s financial support, such as the FiT, is considered. However, with continued instability in governmental support for low carbon sustainable energy, the novel tri-generation system needs to become economically viable in its own right for it to be considered a viable alternative to conventional energy supply. Furthermore, a 2.0kW$_e$ base load capacity is large, and effective electrical utilisation may be problematic, particularly in a domestic building context. With the possibility of future withdrawal of the UK government's financial support for fuel cell CHP technology, maximising in-house electrical consumption will be essential to maintain economic viability. A lower electrical capacity fuel cell would therefore be required. The Japanese domestic market, which is estimated to be ten years ahead of the European market, is now focussing domestic fuel cell CHP development at capacities of 750W$_e$ [2], a possible insight into the future of where European domestic fuel cell development needs to go.

Like other small scale tri-generation systems presented in the literature, the economic performance of the SOFC liquid desiccant tri-generation system is most sensitive to the unit cost of natural gas [20]. The tri-generation system is economically superior compared to the base case system when the unit cost of electricity is greater than 0.24£.kWh^{-1} and as a result Denmark is currently the only country investigated where the tri-generation is economically viable. However, with the extraction of easily accessible fossil fuels diminishing, the unit cost of electricity in many countries is set to continue to rise thus strengthening the economic case of the novel tri-generation system [50].

3.2 Environmental assessment

In this section, an environmental assessment of the novel tri-generation system operating within a UK energy system context is presented. The environmental assessment compares the 1.5kW$_e$ and 2.0kW$_e$ tri-generation system to an equivalent base case system. The evaluation metric used in the environmental assessment is the annual CO_2 emission. This is determined through the multiplication of the annual natural gas and electrical demand by their respective emission factors and summing the result. The emission factors of natural gas and electricity are varied, in a reasonable range, to carry out a sensitivity analysis of the environmental performance. Using electrical emission factor data published by Brander, Sood, Wylie, Haughton, and Lovell [51], the environmental performance of the tri-generation system in the context of different countries is presented. The constants used for the environmental assessment of the novel tri-generation and equivalent base case system are listed in Table 2. The emission factors used are based on a UK energy system context, and are as follows:

- Average natural gas emission factor: 0.184 kg CO_2.kWh^{-1} [42]
- Average electricity emission factor: 0.555 kg CO_2.kWh^{-1} [41]

Table 4 presents the environmental assessment results. The 1.5kW_e and 2.0kW_e tri-generation systems produce a respective 51.3% and 50.2% reduction in annual CO_2 emissions compared to the equivalent base case systems.

Table 4 Environmental assessment results

	Annual emissions (kg CO_2)
1.5kW_e tri	4030
1.5kW_e base	8282
2.0kW_e tri	5756
2.0kW_e base	11567

Figure 11a shows the annual CO_2 emissions of the 1.5kW_e and 2.0kW_e tri-generation systems and equivalent base case systems with respect to natural gas emission factor. Over the investigated natural gas emission factor range of 0.05 to 0.3kgCO_2.kWh^{-1}, the tri-generation system always has a lower annual CO_2 emission. Both the tri-generation and base case systems have a natural gas requirement. However, the greater proportionate natural gas demand in the tri-generation system means its annual CO_2 emission reductions are more sensitive to changes in the natural gas emission factor. Consequently, as the natural gas emission factor is increased, the relative reduction in annual CO_2 emissions compared to the equivalent base case systems is diminished. The

2.0kW_e tri-generation system is more sensitive to changes in the natural gas emission factor than the 1.5kW_e tri-generation system due to a lower electrical efficiency.

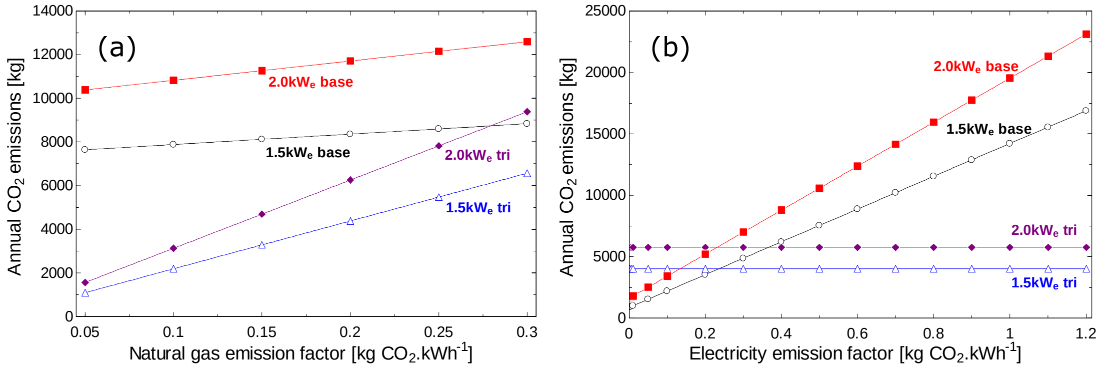

Figure 11 Annual CO_2 emission comparison between the 1.5kW_e and 2.0kW_e tri-generation systems and equivalent base case system with (a) natural gas emission factor, and (b) electricity emission factor

Figure 11b shows the annual CO_2 emissions of the 1.5kW_e and 2.0kW_e tri-generation systems and equivalent base case systems with respect to electrical emission factor. The tri-generation system has no electrical demand, and thus only the base case system is affected by the electrical emission factor. The tri-generation systems have a lower annual CO_2 emission compared to the equivalent base case systems when the electrical emission factor is greater than 0.2363kgCO_2.kWh^{-1} for the 1.5kW_e case and 0.2305kgCO_2.kWh^{-1} for the 2.0kW_e case.

Figure 12 shows the annual CO_2 emissions of the 1.5kW_e and 2.0kW_e equivalent base case systems in a range of different counties using electrical emission factor data published by Brander et al. [51]. The annual CO_2 emissions of the respective tri-generation systems (horizontal lines) are plotted to indicate the countries in which the novel system is currently environmentally viable. The 1.5kW_e and 2.0kW_e tri-generation systems are feasible in all the countries investigated except France and Norway as these countries have an average electrical emission factor of less than 0.1kgCO_2.kWh^{-1}. France and Norway have an energy system that is largely characterised by the use of nuclear and renewables. As a result, the average electrical emission factor is low. Figure 12 shows that the $1.5kW_e$ and $2.0kW_e$ tri-generation system is most environmentally viable in Australia and China. Australia and China generate a large proportion of their electricity from coal, which has a high emission factor per kWh of electricity generated, and thus strengthens the environmental benefit of adopting the novel tri-generation system. Based on the data presented in Figure 9 and Figure 12, Denmark is currently the only country investigated where the novel tri-generation system is both economically and environmentally viable. Interestingly, the countries where the tri-generation system is not economically feasible due to a low electrical unit cost are in general the countries in which the system is most environmentally feasible i.e. Australia and China. This is primarily due to cheap electrical generation from easily accessible, more polluting fuels such as low grade coal.

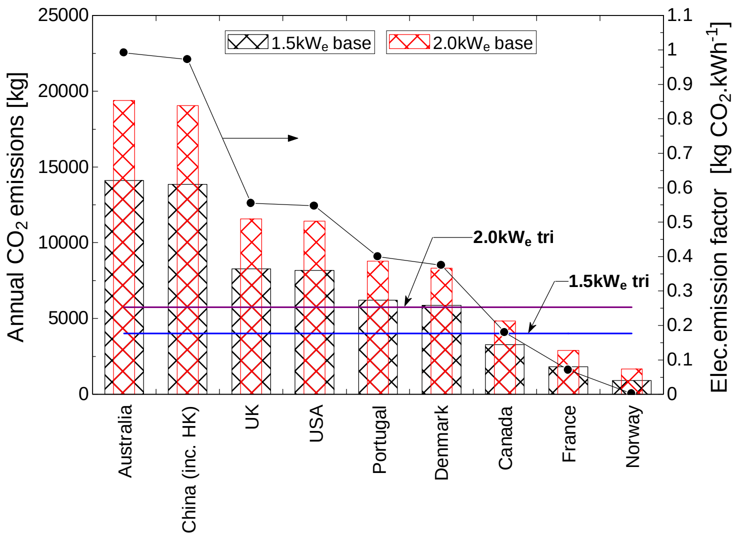

Figure 12 Annual CO_2 emission comparison between the $1.5kW_e$ and $2.0kW_e$ tri-generation systems and equivalent base case system with respect to country of operation

3.2.1 Environmental assessment conclusions

The environmental assessment has demonstrated that the tri-generation system is environmentally viable in almost all scenarios. In a UK energy system context the tri-generation system generates up to 51% annual CO_2 emission reductions compared to the base case. Over the investigated natural gas emission factor range, the tri-generation system is always superior. The tri-generation system’s environmental performance is not directly influenced by changes in the electrical emission factor, however the base case is. As a result, changes in the electrical emission factor have a marked impact on the relative performance of the tri-generation system with respect to the base case system. The tri-generation system is environmentally viable when the electricity emission factor is greater than 0.23kg $CO_2.kWh^{-1}$. France and Norway have a large nuclear and renewable (hydro-electric) energy capacity. As a result, their electricity emission factor is low, and thus the tri-generation system does not provide an environmental benefit in such a setting. Countries such as Australia and China demonstrate the greatest environmental benefit from adopting the novel tri-generation system. As Berger [5] states, the move to a hydrogen economy and with it the transition from the use of hydrocarbon to pure hydrogen-fed fuel cells in the next 30 years provides the potential for highly efficient, zero carbon energy conversion. With such a transition the novel tri-generation system would be highly competitive in almost all scenarios.

4 Conclusions

This paper has served to provide a performance analysis assessment of a novel SOFC liquid desiccant tri-generation system for building applications. Using empirical SOFC and liquid desiccant component data, an energetic, economic and environmental performance analysis assessment of a first-of-its-kind system has been completed. No previous work on such a system has been identified in the literature. With reference to the paper's specific aims set out in the introduction, conclusions of the paper's performance analysis assessment are as follows:

(1) SOFC and liquid desiccant are a viable technological pairing in the development of an efficient and effective tri-generation system. High tri-generation efficiencies in the range of 68-71% are attainable. This is primarily due to the high electrical efficiency of the SOFC and the reasonable COP_{th} of the liquid desiccant system when operating on low grade waste heat.

(2) The inclusion of liquid desiccant air conditioning technology provides an efficiency increase of 9-15% compared to SOFC electrical operation only, demonstrating the potential of the system in building applications that require simultaneous electrical power, heating and/or dehumidification/cooling.

(3) Compared to an equivalent base case system, the tri-generation system is currently only economically viable with a government's financial support. SOFC capital cost and stack replacement are the largest inhibitors to economic viability. Environmental performance is closely linked to electrical emission factor, and thus performance is heavily country dependent.

(4) The countries, in which the system is environmentally viable, are in general the counties in which the system is not economically feasible. This is primarily due to the play off between cheap electrical generation from fossil fuels and more expensive cleaner electrical generation from renewables or nuclear.

(5) The economic and environmental feasibility of the novel tri-generation system will improve with predicted SOFC capital cost reductions and the transition to clean hydrogen production.

Although the novel tri-generation system concept has been demonstrated, future work needs to focus on improving the current unreliability and durability of fuel cell technology, along with reducing its capital cost.

5 Nomenclature

AA_{TC} = Adjusted annual total costs (£)

CFCL = Ceramic Fuel Cells Ltd.

CHP = Combined heat and power

COP_{el} = Electrical coefficient of performance

COP_{th} = Thermal coefficient of performance

$c_{p,WHR}$ = Specific heat capacity of water in WHR circuit ($J.kg^{-1}.K$)

EUAC = Equivalent uniform annual cost (£)

FiT = Feed-in-tariff

η_{elec} = Electrical efficiency (%)

η_{tri} = Tri-generation efficiency (%)

i_f = Inflation factor (%)

i_r = Interest/discount rate (%)

I_{cc} = Initial capital cost (£)

ICE = Internal combustion engine

MCFC = Molten carbonate fuel cell

MRR = Moisture removal rate ($g.s^{-1}$)

$\dot{m}_{WHR}$ = Water mass flow rate in WHR circuit ($kg.s^{-1}$)

n = Year number (Years)

NPC = Net present cost (£)

PAFC = Phosphoric acid fuel cell

PEMFC = Proton exchange membrane fuel cell

PED = Primary energy demand

$\dot{Q}_{cooling}$ = Dehumidifier cooling output (W)

$\dot{Q}_{CH4}$ = Natural gas fuel input (W)

$\dot{Q}_{reg}$ = Regenerator thermal input (W)

$\dot{Q}_{WHR}$ = Waste heat recovered (W)

$\dot{W}_{elec,AC}$ = Net AC electrical power output (W)

SE = Stirling engine

SOFC = Solid oxide fuel cell

SPBP = Simple pay-back period (Years)

SV = Scrap value (£)

T = Temperature (°C)

Tri = Tri-generation

VAS = vapour absorption cooling system

VCS = vapour compression system

WHR = Waste heat recovery

6 Acknowledgements

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7 References

1. DECC, *The Carbon Plan: Delivering our low carbon future*, D.E.a.C. Change, Editor. 2011, Crown: London.

2. Ellamla, H.R., I. Staffell, P. Bujlo, B.G. Pollet, and S. Pasupathi, *Current status of fuel cell based combined heat and power systems for residential sector.* Journal of Power Sources, 2015. **293**(0): p. 312-328.

3. Jradi, M. and S. Riffat, *Tri-generation systems: Energy policies, prime movers, cooling technologies, configurations and operation strategies.* Renewable and Sustainable Energy Reviews, 2014. **32**(0): p. 396-415.

4. Elmer, T., M. Worall, S. Wu, and S.B. Riffat, *Fuel cell technology for domestic built environment applications: State of-the-art review.* Renewable and Sustainable Energy Reviews, 2015. **42**(0): p. 913-931.

5. Berger, R., *Advancing Europe's energy systems: Stationary fuel cells in distributed generation*, F.C.a.H.J. Undertaking, Editor. 2015, Publications Office of the European Union 2015: Luxembourg.

6. Elmer, T., M. Worall, S. Wu, and S.B. Riffat, *Emission and economic performance assessment of a solid oxide fuel cell micro-combined heat and power system in a domestic building.* Applied Thermal Engineering, 2015. **90**: p. 1082-1089.

7. Jradi, M. and S. Riffat, *Experimental investigation of a biomass-fuelled micro-scale tri-generation system with an organic Rankine cycle and liquid desiccant cooling unit.* Energy, 2014. **71**(0): p. 80-93.

8. Liu, X.H., Geng, K. C., Lin, B. R., Jiang, Y., *Combined cogeneration and liquid-desiccant system applied in a demonstration building.* Energy and Buildings, 2004. **36**(9): p. 945-953.

9. Wu, J.Y., J.L. Wang, S. Li, and R.Z. Wang, *Experimental and simulative investigation of a micro-CCHP (micro combined cooling, heating and power) system with thermal management controller.* Energy, 2014. **68**(0): p. 444-453.

10. Minciuc, E., O. Le Corre, V. Athanasovici, and M. Tazerout, *Fuel savings and CO2 emissions for tri-generation systems.* Applied Thermal Engineering, 2003. **23**(11): p. 1333-1346.

11. Al-Sulaiman, F.A., F. Hamdullahpur, and I. Dincer, *Trigeneration: A comprehensive review based on prime movers.* INTERNATIONAL JOURNAL OF ENERGY RESEARCH, 2011. **35**(3): p. 233-258.

12. Deng, J., R.Z. Wang, and G.Y. Han, *A review of thermally activated cooling technologies for combined cooling, heating and power systems.* Progress in Energy and Combustion Science, 2011. **37**(2): p. 172-203.

13. Yu, Z., J. Han, X. Cao, J. Han, X. Cao, W. Chen, and B. Zhang, *Analysis of total energy system based on solid oxide fuel cell for combined cooling and power applications.* International Journal of Hydrogen Energy, 2010. **35**(7): p. 2703-2707.

14. Yu, Z., Han, Jitian., Cao, Xianqi, *Investigation on performance of an integrated solid oxide fuel cell and absorption chiller tri-generation system.* International Journal of Hydrogen Energy, 2011. **36**(19): p. 12561-12573.

15. Margalef, P. and S. Samuelsen, *Integration of a molten carbonate fuel cell with a direct exhaust absorption chiller.* Journal of Power Sources, 2010. **195**(17): p. 5674-5685.

16. Al-Sulaiman, F.A., I. Dincer, and F. Hamdullahpur, *Energy analysis of a trigeneration plant based on solid oxide fuel cell and organic Rankine cycle.* International Journal of Hydrogen Energy, 2010. **35**(10): p. 5104-5113.

17. Fong, K.F. and C.K. Lee, *Investigation on zero grid-electricity design strategies of solid oxide fuel cell trigeneration system for high-rise building in hot and humid climate.* Applied Energy, 2014. **114**(0): p. 426-433.

18. Zink, F., Lu, Yixin, Schaefer, Laura, *A solid oxide fuel cell system for buildings.* Energy Conversion and Management, 2007. **48**(3): p. 809-818.

19. Darwish, M.A., *Building air conditioning system using fuel cell: Case study for Kuwait.* Applied Thermal Engineering, 2007. **27**(17–18): p. 2869-2876.

20. Huangfu, Y., J.Y. Wu, R.Z. Wang, X.Q. Kong, and B.H. Wei, *Evaluation and analysis of novel micro-scale combined cooling, heating and power (MCCHP) system.* Energy Conversion and Management, 2007. **48**(5): p. 1703-1709.

21. Mı́guez, J.L., S.P. Murillo, J., , and L.M. López, *Feasibility of a new domestic CHP trigeneration with heat pump: I. Design and development.* Applied Thermal Engineering, 2004. **24**(10): p. 1409-1419.

22. Kong, X.Q., R.Z. Wang, J.Y. Wu, X.H. Huang, Y. Huangfu, D.W. Wu, and Y.X. Xu, *Experimental investigation of a micro-combined cooling, heating and power system driven by a gas engine.* International Journal of Refrigeration, 2005. **28**(7): p. 977-987.

23. Pilatowsky, I., R.J. Romero, C.A. Isaza, S.A. Gamboa, P.J. Sebastian, and W. Rivera, *Cogeneration Fuel Cell - Sorption Air Conditioning Systems*. Green Energy and Technology. 2011, London: Springer.

24. Porteiro, J., Mı́guez, J. L., Murillo, S., López, L. M., *Feasibility of a new domestic CHP trigeneration with heat pump: II. Availability analysis.* Applied Thermal Engineering, 2004. **24**(10): p. 1421-1429.

25. Pilatowsky, I., R.J. Romero, C.A. Isaza, S.A. Gamboa, W. Rivera, P.J. Sebastian, and J. Moreira, *Simulation of an air conditioning absorption refrigeration system in a co-generation process combining a proton exchange membrane fuel cell.* International Journal of Hydrogen Energy, 2007. **32**(15): p. 3174-3182.

26. Najafi, B., S. De Antonellis, M. Intini, M. Zago, F. Rinaldi, and A. Casalegno, *A tri-generation system based on polymer electrolyte fuel cell and desiccant wheel – Part A: Fuel cell system modelling and partial load analysis.* Energy Conversion and Management, 2015. **106**: p. 1450-1459.

27. Intini, M., S. De Antonellis, C.M. Joppolo, and A. Casalegno, *A trigeneration system based on polymer electrolyte fuel cell and desiccant wheel – Part B: Overall system design and energy performance analysis.* Energy Conversion and Management, 2015. **106**: p. 1460-1470.

28. Gigliucci, G., Petruzzi, L., Cerelli, E., Garzisi, A., La Mendola, A., *Demonstration of a residential CHP system based on PEM fuel cells.* Journal of Power Sources, 2004. **131**(1–2): p. 62-68.

29. Al-Sulaiman, D. F. A., I., , and F. Hamdullahpur, *Exergy analysis of an integrated solid oxide fuel cell and organic Rankine cycle for cooling, heating and power production.* Journal of Power Sources, 2010. **195**(8): p. 2346-2354.

30. Bhatti, M.S., J.F. O'Brien, I. Reyzin, M. Grieve, and S.M. Kelly, *Solid oxide fuel cell assisted air conditioning system*. 2010: USA.

31. Jeong, J., S. Yamaguchi, K. Saito, and S. Kawai, *Performance analysis of desiccant dehumidification systems driven by low-grade heat source.* International Journal of Refrigeration, 2011. **34**(4): p. 928-945.

32. Tse, L.K.C., S. Wilkins, N. McGlashan, B. Urban, and R. Martinez-Botas, *Solid oxide fuel cell/gas turbine trigeneration system for marine applications.* Journal of Power Sources, 2011. **196**(6): p. 3149-3162.

33. Wang, Y., Y. Huang, E. Chiremba, A.P. Roskilly, N. Hewitt, Y. Ding, D. Wu, H. Yu, X. Chen, Y. Li, J. Huang, R. Wang, J. Wu, Z. Xia, and C. Tan, *An investigation of a household size trigeneration running with hydrogen.* Applied Energy, 2011. **88**(6): p. 2176-2182.

34. Srikhirin, P., S. Aphornratana, and S. Chungpaibulpatana, *A review of absorption refrigeration technologies.* Renewable and Sustainable Energy Reviews, 2001. **5**(4): p. 343-372.

35. Gandhidasan, P., *A simplified model for air dehumidification with liquid desiccant.* Solar Energy, 2004. **76**(4): p. 409-416.

36. Elmer, T., M. Worall, S. Wu, and S. Riffat, *An experimental study of a novel integrated desiccant air conditioning system for building applications.* Energy and Buildings, 2016. **111**: p. 434-445.

37. Sommer, K., Messenholler, E. *Practical experience with a fuel cell unit for Combined Heat and Power (CHP) generation on the building level*. REHVA Journal, 2013. **12**.

38. Foger, K. *The Technology of Ceramic Fuel Cells*. Electrical Developments, 2013. 48-51.

39. Elmer, T., M. Worall, S. Wu, and S. Riffat, *Experimental evaluation of a liquid desiccant air conditioning system for tri-generation/waste-heat-driven applications.* International Journal of Low-Carbon Technologies, 2016.

40. Goot, G. *Electricity Price per kWh (2013)*. 2013 [cited 2014 06/03/2014]; Available from: http://blog.comparemysolar.co.uk/electricity-price-per-kwh-2013-comparison-of-e-on-edf-npower-british-gas-scottish-and-sse/.

41. AMEE. *realtime carbon*. 2014 [cited 2014 06/04/2014]; Available from: http://realtimecarbon.org/.

42. EST. *Energy Saving Trust - Our Calculations*. 2014; Available from: http://www.energysavingtrust.org.uk/Energy-Saving-Trust/Our-calculations.

43. Buker, M.S., B. Mempouo, and S.B. Riffat, *Experimental investigation of a building integrated photovoltaic/thermal roof collector combined with a liquid desiccant enhanced indirect evaporative cooling system.* Energy Conversion and Management, 2015. **101**: p. 239-254.

44. Welch, T., *CIBSE Knowledge Series: KS13 - Refrigeration*, H. Carwarardine and K. Butcher, Editors. 2008, CIBSE Publications.

45. IEA *Electricity Information*. IEA Statistics, 2012.

46. CFCL. *Electronic resource: CFCL BlueGEN Modular Generator - Power and Heat*. Electronic resource [Electronic resource] 2009 08/12/2012; Available from: http://www.bluegen.info/Assets/Files/BlueGen_Brochure_(ENG_GER)_April_2010.pdf.

47. DECC. *CHP Incentives - Feed-in Tariff*. 2014 [cited 2014 06/04/2014]; Available from: http://chp.decc.gov.uk/cms/feed-in-tariff/.

48. Infante Ferreira, C. and D.-S. Kim, *Techno-economic review of solar cooling technologies based on location-specific data.* International Journal of Refrigeration, 2014. **39**: p. 23-37.

49. Staffell, I. and R. Green, *The cost of domestic fuel cell micro-CHP systems.* International Journal of Hydrogen Energy, 2013. **38**(2): p. 1088-1102.

50. DECC, *Estimated impacts of energy and climate change policies on energy prices and bills*, D.o.E.a.C. Chnage, Editor. 2013, Crown Copyright: London.

51. Brander, M., A. Sood, C. Wylie, A. Haughton, and J. Lovell *Technical Paper | Electricity-specific emission factors for grid electricity*. Ecometrica, 2011.