Financial, Environmental and Energy Analysis of Various Micro-CHP Systems within the UK Domestic Market

T. S. Doyle, Z. Dehouche, A. Harries, and I. Rizos

Abstract—**Widespread uptake of decentralized energy production has the potential to reduce carbon emissions whilst making the energy market more affordable, sustainable and robust. The application of micro-CHP systems in the domestic market has the potential to alleviate pressure on the national grid by displacing electrical and heating demands, and also through the export of excess electricity. Initial market support for this has been shown by the UK's Feed-in-tariff scheme which is currently incentivizing efficient micro-CHP systems (<2kW) by providing a financial return for every unit of electrical energy produced and further reward for every unit exported to the grid. It is the aim of this research to attempt to identify those m-CHP systems available on the market and to quantify the expected benefits in terms of cost, CO_2 savings and overall energy efficiency when feeding a typical domestic property in the UK. In an attempt to maximize financial income from the FIT scheme an operating strategy of constant supply, at the maximum rated output, is compared against the conventional heat led approach most often used in CHP applications. Overall results indicate that the heat-to-power ratio for a given m-CHP has a direct impact on all of the performance factors being measured and also determines the preferred operating strategy that should be followed.**

Index Terms—**Distributed generation, energy efficiency, feed-in-tariff, m-CHP.**

I. INTRODUCTION

Combined heat and power (CHP) systems are designed to utilize the useful heat and electrical energy produced from a single source, and near the point of use. Environmental and economical benefits are a result of reduced fuel consumption and emissions whilst increasing overall energy efficiency. Considering existing centralized energy plants lose two thirds of their energy to the atmosphere, in the form of heat, along with further losses caused by distribution. The advantages of distributed power generation in small decentralized units are becoming ever more apparent. The implementation of CHP systems is actively being promoted in Europe through the Cogeneration Directive 2004/08/EC where the initial objectives were to deliver primary energy savings but has grown in importance as the climate agenda has become more of a concern. By reducing the scale of these systems (~2kWe) these micro-CHP appliances can be installed at the point of use within a domestic environment and can be fuelled by conventional natural gas supplies. Producing onsite

electricity means centrally generated electricity is displaced and by utilizing the heat produced to supply domestic hot water and space heating demands further savings in overall gas consumption can be made.

In order for us to fully understand the benefits of such systems it is important to explore the environmental and economic factors that will decide their commercial success. In recognition of the potential to reduce carbon emissions attributed to the households the UK government is supporting the uptake of m-CHP (<2kW) through the national feed-in-tariff (FIT) scheme which is due to be increased from 11p/kWh to 12.5p/kWh [1] (at time when all other tariffs are being reduced). The common technologies used in the category of m-CHP are; internal combustion engines (ICE), Stirling engines, organic Rankine cycle and fuel cells. Table I illustrates the various products currently available in the sub-2kW m-CHP market.

Due to their high electrical efficiencies, low noise and gas emissions fuel cells are a very attractive option as residential m-CHP systems. There is now a high temperature fuel cell unit that is commercially available and is accredited under the UK's Micro Generation Scheme (MCS) making this product eligible for the UK feed-in-tariff. This elevates the status of this technology out of the stage of research and development and now faces the challenges associated with new technologies entering into the market.

II. METHODOLOGY

This paper will look to evaluate the performance of the products specified in Table I whilst supplying a load which is representative of a typical home found in the UK. Electrical and domestic hot water (DHW) loads were obtained from a study carried out by the International Energy Agency Energy Conservation in Buildings and Community Systems (ECBCS) under the title COGEN-SIM and published results are presented in Annex 42 [2]. The electrical demand profile from the study was obtained from actual readings of a 65m² home in Newcastle. The DHW profile represents a 200 l/day consumption rate where values have been obtained from probability functions with the assumption that the temperature of the water is increased by 35°C relative to the inlet feed temperature. Space heating demands have been generated through thermal modelling using TAS software developed by Environmental Design Solutions Limited [3]. In order to represent a building similar to that of the property monitored in Newcastle u-values representing pre-1980 domestic constructions were obtained from the National Calculation Method (NCM) as defined by the Department for Communities and Local Government which provides a database of constructions and services for evaluating the

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performance of a building's energy consumption. Building layouts were obtained using information published by the Energy Savings Trust [4], [5] and a floor plan of a typical semi-detached house was used. See Table II for a summary of the constructions used for the various building elements and the subsequent thermal properties calculated by the software.

TABLE I: MARKET SUMMARY OF AVAILABLE M-CHP SYSTEMS WITH THEIR RESPECTIVE PERFORMANCE VALUES

Brand	Product	Technology	Electrical output kW(eff)	Thermal output kW(eff)	Overall efficiency	Fuel
Whisper Tech Limited	WhisperGen	Stirling engine	1.2(12%)	12(78%)	90%	NG
Stirling systems	SEM	Stirling engine	1.2(18%)	5(72%)	90%	NG
Baxi	Ecogen	Stirling engine	1.1(9%)	24(83%)	92%	NG
Baxi	Innotech	PEMFC	1(32%)	1.8(59%)	91%	NG
Otag	Lion-powerblock	Rankine engine	2(12%)	16(73%)	85%	NG
EnergetixGenlec	Kingston	Rankine engine	1(12%)	6.8(78%)	90%	NG, LPG
Climate Energy	freewatt (Honda)	ICE	1.2(26%)	2.7(59%)	85%	NG, LPG
Valliant	EcoPOWER (Honda)	ICE	1(26%)	2.5(66%)	92%	NG, LPG
CFCL	Bluegen	SOFC	1.5(60%)	0.54(25%)	85%	NG
Natural Gas (NG), Liquid Petroleum Gas (LPG)						

TABLE II: DESCRIPTION OF CONSTRUCTION LAYERS AND MATERIALS APPLIED TO VARIOUS BUILDING ELEMENTS FOR THERMAL MODELLING

| Building Element	Construction layers and materials	u-value (W/m^2.°C)
Ground floor	50mm flooring screed, 10mm insulation, 100mm concrete, 25mm brick slips, underfloor clay	0.849
External wall	102mm brick, 50mm air layer, 100mm brick, 13mm dense plaster	1.287
Internal wall	100mm concrete block, 25mm air layer, 60mm insulation, 13mm plasterboard	0.821
Pitched roof	9.5mm plasterboard, 200mm insulation, 1m loft space, 10mm concrete tiles	0.178
Suspended floor	30mm plywood, 20mm insulation, 35mm air layer, 100mm concrete	0.532
PVC double glazing	PVC frame with two hollow chambers, 4mm clear glass, 6mm air layer, 4mm clear glass	3.297
External door	9mm plywood, 25mm insulation, 9mm plywood	0.755
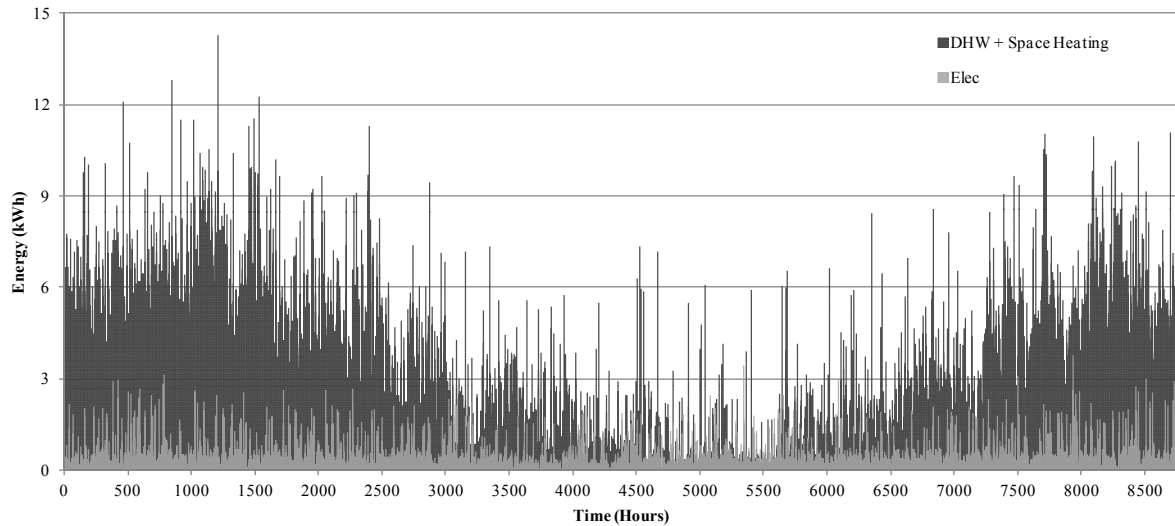
Fig. 1. The graph represents the annual fluctuations in the heating demand, comprising of the DHW and space heating requirements, as well as the electrical demand for an average domestic property in the UK with a total annual heating demand of 16,406kWh and electrical demand of 3028kWh.

Fig. 1 illustrates the annual heating and electrical demand profile for a typical domestic property in the UK. The annual electrical consumption stands at 3,028kWh and the heating demand, divided into DHW and space heating stands at 2,980kWh and 13,425kWh respectively, and in terms of the property the annual contribution from each is 69% towards space heating and 16% and 15% for electrical and DHW respectively. These values are consistent with UK's gas and electricity regulator Ofgem who use typical medium consumption figures of 3,300kWh and 16,500kWh for

electricity and gas respectively [6].

The main objective of this study is to compare the energy, financial and environmental performance of a home with and without the application of a m-CHP system and how incentives such as the UK's FIT scheme can contribute to their widespread uptake.

To do this successfully the performance of this typical home must be identified according to the standard grid efficiency, unit price per kWh for electricity and gas and CO_2 emission factors associated with the consumption of both

electricity and gas. For a summary of these values please refer to Table III. According to information published by the UK's Department of Energy and Climate Change (DECC) the total primary energy (including renewables) used for the production of electricity in 2012 for the UK was 901.3TWh and the total amount of electricity delivered to the consumer was 320.5TWh [7]. This amounts to an overall efficiency of 35.6% for the electricity supplied from the grid.

III. RESULTS AND DISCUSSION

With this hourly energy information for the building we can begin to analyze the performance of the building and we shall begin by applying the variables set out in Table III to describe the financial, environmental and energy performance for the given loads.

TABLE III: INFORMATION DESCRIBING THE COST AND PERFORMANCE OF THE UK NATION GRID

UK Grid		
Electrical Efficiency (%)	35.6	
Average boiler efficiency (%)	79	[8][9]
Unit cost for electricity (p/kWh)	12.79	[10]
Unit cost for gas (p/kWh)	4.05	[11]
CO_2 factor for electricity (kgCO$_2$/kWh)	0.5246	[12]
CO_2 factor for gas (kgCO$_2$/kWh)	0.1836	[12]
Gross calorific value for natural gas (MJ/m3)	39.4	[13]
UK Feed-in-tariff scheme for m-CHP (<2kW)		
Generation (p/kWh)	12.5	[14]
Export (p/kWh)	4.5	[14]

In comparison we must understand how the m-CHP systems described in Table I will influence the values expressed in Table IV. For this comparison we assume all excess electricity is exported to the grid and excess heat is stored in a hot water storage tank which incurs a heat loss of 10% per hour. The m-CHP system will be installed along with the existing boiler that will be used to cope with any demand that cannot be met by the m-CHP and hot water storage tank, and similarly electricity will be imported to make up for any shortfall in electrical supply. Also, to be considered is the operating strategy of the m-CHP unit as conventional CHP systems are heat led but systems such as the high temperature fuel cell are required to run at a constant supply. So for the purpose of this analysis one representative technology from the above systems will be operated at constant supply and as a comparison will also operate as conventional heat led systems which will give us an opportunity to evaluate the best strategy to adopt in terms of financial payback using the FIT scheme, environmental CO_2 emissions and overall system efficiency.

TABLE IV: RESULTING ENERGY BILL, CO_2 EMISSIONS AND SYSTEM EFFICIENCY FOR A TYPICAL UK HOME

	Energy bill	Total CO_2 emissions	System Efficiency
Electricity	£387	1,589 kg	35.6%
Gas	£841	3,012 kg	79.0%
Overall	£1,228	4,601 kg	72.2%

A. Whispergen

It is clear to see that the m-CHP systems with high heat-to-power ratios such as the Stirling engine based Whispergen are far better off operating under the heat led strategy. In terms of meeting the demand and efficiency, illustrated in Fig. 2 a) and b), the heat led strategy enables the unit to meet 99% of the building's heat demand but only 44% of the electrical and allows the unit to maintain a high level of efficiency with the total household efficiency, including imported backup electricity and gas, standing at 85%, as seen in Table V. This is supported by the financial analysis, shown in Fig. 2 c) and d) which shows that when the Whipsergen is heat led the total grid cost is constantly below the cost expected without the m-CHP unit which will provide an annual financial saving of 43% and an overall CO_2 saving of 16%. During constant supply the unit generates a large amount of heat that cannot be utilized by the building and therefore has a detrimental effect on the system efficiency and operating cost of the unit.

B. EcoPOWER

The reduced heat-to-power ratio of the ICE EcoPower unit shows a smaller performance gap between heat led and constant operation strategy, seen in Fig. 3 a) and b), and the decision on which strategy is most suitable is not clear as the heat led strategy meets only 63% and 60% of the heating and electrical load whilst the constant supply strategy supplies 79% and 91% of the heating and electrical requirements. Also, operating at constant supply the unit indicates a greater financial saving of 83% compared to 60% for the heat led, and the CO_2 savings marginally favor the heat led strategy with a 21% saving compared to 15% for the constant supply. So environmentally the heat led strategy is best but if cost is the main driver the constant supply would be favored, it is important to mention that these financial benefits are due to the FIT and that without the FIT the heat led strategy would be the best strategy to adopt, as illustrated in Fig. 3 c) and d).

TABLE V: RESULTING ENERGY BILL, CO_2 SAVINGS AND EFFICIENCY FOR A TYPICAL UK HOME

	Whispergen		EcoPOWER		Bluegen
	Heat led	Constant	Heat led	Constant	Constant
Gas cost (m-CHP)	£842	£3,546	£637	£1,364	£886
FIT - generation	£ 312	£1,314	£ 511	£1,095	£1,643
FIT - export	£52	£345	£103	£270	£460
Grid import (Gas&Elec)	£226	£25	£465	£213	£618
Total cost/income	£ 703	£1,911	£487	£212	£598
CO_2 savings	16%	-74%	21%	15%	36%
Overall household efficiency	85%	31%	83%	61%	78%

Underlined values indicate income rather than expense. Constant indicates the unit operates continually at the maximum rated output.
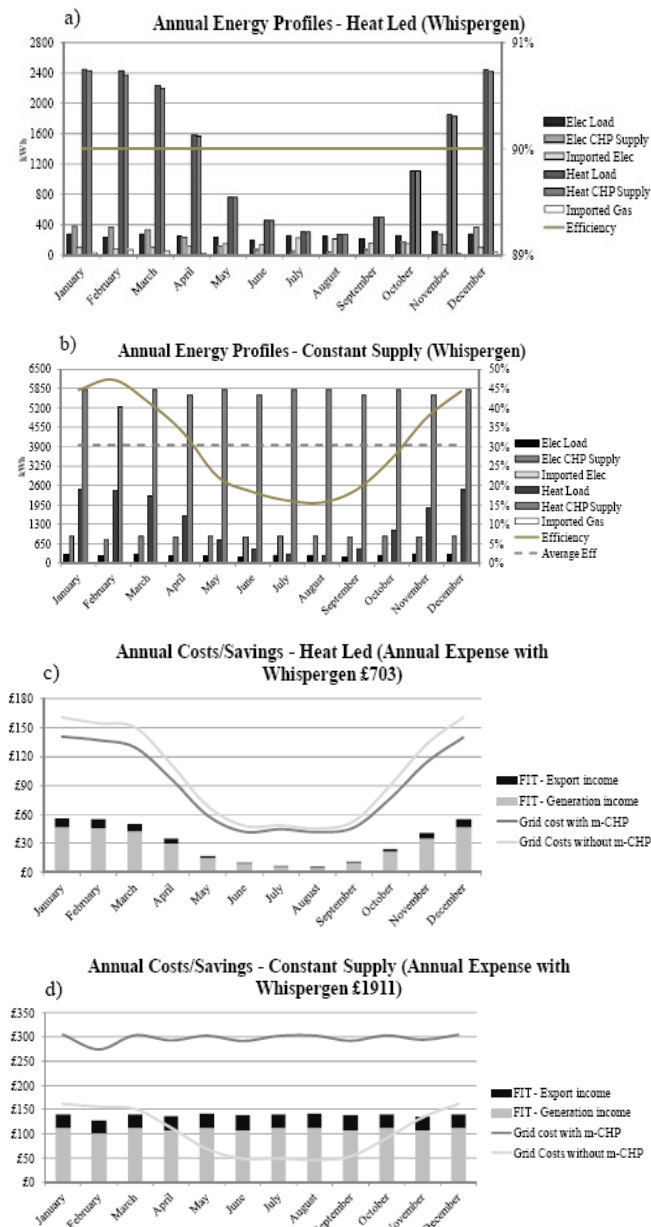
Fig. 2. Graphs a) and b) illustrate the monthly quantities of demand and supply of the home and Whispergenas well excess energy imported to meet peak demands outside of the m-CHP's rated capacity, the overall monthly system efficiency is also plotted. Graphs c) and d) represent the financial incomes and expenses according to the unit cost of gas and electricity and the UK's FIT scheme with and without the m-CHP.

A. Bluegen

The high temperature fuel cell Bluegen unit offers the lowest heat-to-power ratio of all the technologies tested and the results in Fig 4 a) indicate a very high level of efficiency throughout the year with an expected drop in the summer where there is insufficient demand for the heat produced. The constant supply of heat only satisfies 28% of the heating demand, which is why an installation of this kind would require a secondary gas boiler or an electric immersion heater providing further heating to the hot water storage tank whilst utilizing the m-CHP's constant electrical output. The unit satisfies 97% of the annual electrical demand and benefits greatly from the FIT scheme as the unit will provide an annual income of £598 which equates to a financial saving of 149%, again this is solely due to the FIT and if we study the grid cost lines in Fig 4 b) it can be seen that without the FIT the unit would cost more to run compared to the existing grid

connection. Therefore for this system to be commercially competitive a long term tariff will be required for the power produced and/or there will need to be an increase in the grid price for electricity. Along with the substantial financial savings Bluegen unit will also provide a CO_2 saving of 36% and an overall household efficiency of 78%.
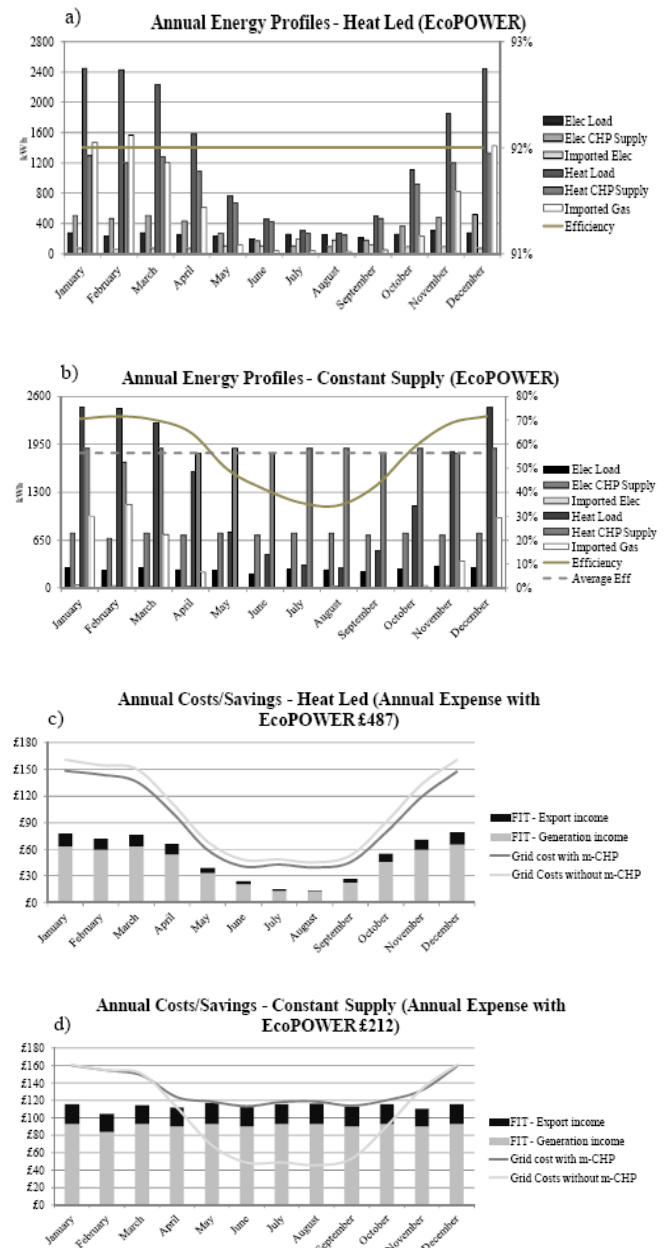

Fig 3. Similar to the Whispergen graphs of the EcoPOWER unit displays higher operating efficiency during both heat led and constant supply operating strategy seen in a) and b). This benefit also influences the financial cost of the unit as seen in c) and d) both values are lower than the Whispergen with the constant supply being the most cost effective, although not without the support of the FIT.
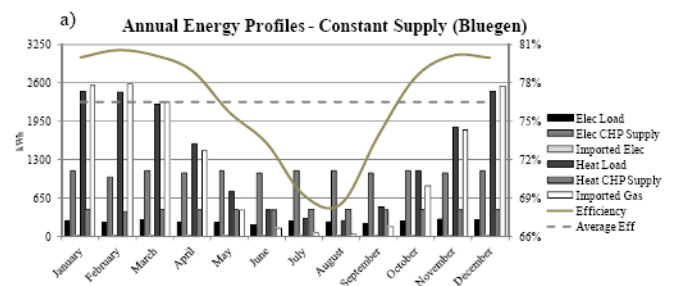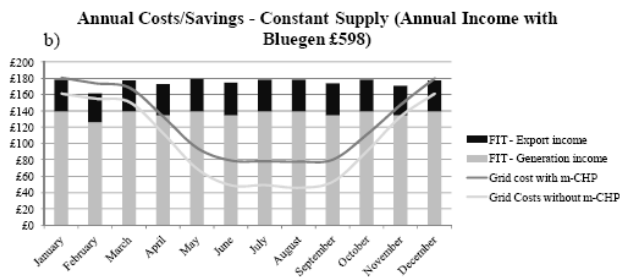
Fig. 3. The high temperature fuel cell is only measured under constant supply as this is the standard operating procedure used in order to protect the lifespan of the unit. The surplus heat generated over the summer months clearly has an effect on the operating efficiencies and is clearly illustrated in a). In b) we can see the benefit of the increased electrical capacity which results in a financial income owing to the UK's FIT.

IV. CONCLUSIONS

The factors influencing the feasibility of the m-CHP system studied have shown to be the heat-to-power ratio as this has a direct influence on the optimal operating strategy. It can be seen that those m-CHP units with high heat-to-power ratios benefit from being heat led as operating costs are reduced, even before accounting for the financial income generated through the FIT, and CO_2 savings are far greater compared to being run at constant supply. Reducing the heat-to-power ratio has shown to have similar cost savings when run as heat led but whenincluding savings generated through the FIT, because more electricity is being produced, overall costs are further reduced. The high temperature fuel cell with its much lower heat-to-power ratio is the only unit which sees a positive income for the year and because of the reduced amount of heat produced can successfully be run at constant supply resulting in the unit constantly generating income. It is also interesting to note that the percentage of CO_2 savings steadily increases with reduced heat-to-power ratio. This can be attributed to the difference in grid supplied electrical efficiency and heat supplied by a supplement boiler which in this study operates with a 79% efficiency.By minimizing the heat generated over the summer period with a low heat-to-power ratio losses can be reduced whilst allowing the m-CHP unit to operate at constant supply.

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