2014-5

Economic, Energy and GHG Emissions Performance Evaluation of a Whispergen Mk IV Stirling engine µ-CHP unit in a domestic dwelling

Gerry Conroy
Technological University Dublin, gerry.conroy@tudublin.ie

Aidan Duffy
Technological University Dublin, aidan.duffy@tudublin.ie

Lacour Ayompe
Technological University Dublin, lacour.ayompe@tudublin.ie

Recommended Citation

Conroy, G., Duffy, A. & Ayompe, L. (2014) Economic, Energy and GHG Emissions Performance Evaluation of a WhisperGen Mk IV Stirling Engine µ-CHP Unit in a Domestic Dwelling, *Energy Conversion and Management,* Vol. 81, pp. 465-474, ISSN 0196-8904, doi:10.1016/j.enconman.2014.02.002

Elsevier Editorial System(tm) for Energy Conversion and Management
Manuscript Draft

Manuscript Number: ECM-D-13-01156R2

Title: Economic, energy and GHG emissions performance evaluation of a Whispergen Mk IV Stirling engine μ-CHP unit in a domestic dwelling

Article Type: Original research paper

Section/Category: 1. Energy Conservation and Efficient Utilization

Keywords: μ-CHP; Stirling engine; condensing gas boiler; WhisperGen; microgeneration.

Corresponding Author: Dr. Lacour M. Ayompe, PhD

Corresponding Author's Institution: Dublin Institute of Technology

First Author: Lacour M. Ayompe, PhD

Order of Authors: Lacour M. Ayompe, PhD; Gerry Conroy; Aidan Duffy, PhD

Abstract: This paper presents an assessment of the energy, economic and greenhouse gas emissions performances of a WhisperGen Mk IV Stirling engine μ-CHP unit for use in a conventional house in the Republic of Ireland. The energy performance data used in this study was obtained from a field trial carried out in Belfast, Northern Ireland during the period June 2004 - July 2005 by Northern Ireland Electricity and Phoenix Gas working in collaboration with Whispertech UK. A comparative performance analysis between the μ-CHP unit and a condensing gas boiler revealed that the μ-CHP unit resulted in an annual cost saving of €180 with an incremental simple payback period of 13.8 years when compared to a condensing gas boiler. Electricity imported from the grid decreased by 20.8% while CO2 emissions decreased by 16.1%. The μ-CHP unit used 2,889 kWh of gas more than the condensing gas boiler.

Suggested Reviewers: Viktor Dorer
viktor.dorer@empa.ch

Hongbo Ren
tjrhb@hotmail.com

M. Sasso
sasso@unisannio.it

Highlights (for review)

- The performance of a Stirling engine MK IV micro-CHP unit was evaluated in a domestic dwelling in Ireland
- The performance of the micro-CHP was compare to that of a condensing gas boiler
- The micro-CHP unit resulted in an annual cost saving of €180 compared to the condensing gas boiler
- Electricity imported from the grid decreased by 20.8% while CO_2 emissions decreased by 16.1%
- The micro-CHP unit used 2,889 kWh of gas more than the condensing gas boiler during one year of operation

18th January, 2014

The Editor
Energy Conversion and Management Journal

Dear Editor,

Please find attached the second revision to our manuscript titled "Economic, energy and GHG emissions performance evaluation of a Whispergen Mk 4 Stirling engine µ-CHP unit in a domestic dwelling" for publication in Energy Conversion and Mnagerment Journal. The manuscript contains 7 figures and 4 tables.

The authors of the paper and their affiliations are:

G. Conroy
School of Civil & Building Services Engineering, Dublin Institute of Technology, Dublin 1, Ireland
A. Duffy and **L.M. Ayompe**
School of Civil & Building Services Engineering and Dublin Energy Lab, Dublin Institute of Technology, Dublin 1, Ireland.

Kind regards,

Dr. L.M. Ayompe
Postdoctoral Researcher
School of Civil and Building Services Engineering
Dublin Institute of Technology
Dublin 1

Economic, energy and GHG emissions performance evaluation of a Whispergen Mk 4IV Stirling engine μ-CHP unit in a domestic dwelling

G. Conroy, A. Duffy[1]* and L.M. Ayompe*
School of Civil & Building Services Engineering, Dublin Institute of Technology, Dublin 1, Ireland.
*School of Civil & Building Services Engineering and Dublin Energy Lab, Dublin Institute of Technology, Dublin 1, Ireland.

Abstract

This paper presents an assessment of the energy, economic and greenhouse gas emissions performances of a WhisperGen Mk IV Stirling engine μ-CHP Mk 4 unit for use in a conventional house in the Republic of Ireland. The energy performance data used in this study was obtained from a field trial carried out in Belfast, Northern Ireland during the period June 2004 - July 2005 by Northern Ireland Electricity and Phoenix Gas working in collaboration with Whispertech UK. A comparative performance analysis between the μ-CHP unit and a condensing gas boiler revealed that the μ-CHP unit resulted in an annual cost saving of €180 with an incremental simple payback period of 13.8 years when compared to a condensing gas boiler. Electricity imported from the grid decreased by 20.8% while CO_2 emissions decreased by 2.316.1%. The μ-CHP unit used 2,889 kWh of gas more than the condensing gas boiler.

Keywords: μ-CHP, Stirling engine, condensing gas boiler, WhisperGen, microgeneration

1. Introduction

One of the greatest challenges mankind faces today is the fight against climate change. Renewable and sustainable energy technologies have the potential to reduce greenhouse gas (GHG) emissions, increase economic competitiveness and enhance security of supply. In

[1] Corresponding author: Email: aidan.duffy@dit.ie
Tel: +353 14023940

Europe, the EU27 member states have committed to an overall 20% reduction in GHG emissions (compared to 1990 levels) and a 20% improvement in energy efficiency by 2020. The residential sector accounted for 26.5% of EU energy requirements in 2009, second only to transport at 33.2%. Direct CO_2 emissions from the sector were 431.9 $MtCO_2$ which accounted for 10.7% of the total CO_2 emissions within the EU [1]; this proportion increases to 20-30% when direct emissions from energy conversion processes (excluding emissions from electricity) are included. This sector therefore has great potential to contribute to the EU's greenhouse gas emissions reduction targets. However, any policy initiatives in the sector require a thorough analysis of the CO_2 emissions reduction potential of different energy efficient and microgeneration technologies such as micro combined heat and power (μ-CHP), fuel cells, solar water heaters, photovoltaic systems and biomass boilers which can supply heat and electricity with reduced CO_2 emissions.

μ-CHP units are localised power generating stations producing both heat and electricity at the point of use and can export excess electricity generated if connected to the national grid. The thermal output is used for hot water and space heating while the AC electricity is used locally in the house or, if demand is sufficiently low, is fed onto the local distribution system. They are especially suited to situations where there is simultaneous heat and power demand as is prevalent in houses in northern European countries. The benefits of μ-CHP units include [2]:

- high overall energy conversion efficiency (in excess of 90% for Stirling engines);
- very low noise and vibration levels; and
- very low emissions of NOx, COx, SOx and particulates.

Typical operating efficiencies for μ-CHP units are between 80 to 90% compared with less than 40% of primary energy input for conventional power generating systems that supply electricity to the grid. CHP technologies fall into three groups: internal combustion engines, external combustion engines (e.g. Stirling cycle) and fuel cells.

There are several manufacturers of combined heat and power (CHP) units in the market and although the technology is developing, there are very few μ-CHP units available to buy. The main suppliers of internal combustion engine CHP units include Baxi Dachs [3] and Honda Ecowill [4]. The Baxi Dachs produces 12 kW of heat and 5 kW of electricity. The Honda Ecowill produces 2.5 kW of heat and 1 kW of electrical power and can only be fitted in parallel with a conventional boiler in a domestic dwelling because of its low energy production capacity. Leading suppliers of external combustion engines include Baxi Dachs, Whispertech and Worcester Bosch. Whispertech (New Zealand) developed the WhisperGen Stirling engine which generates 1 kW of electricity (kW_e) and 8 kW of heat (kW_{th}). Worcester Bosch's unit is the Worcester Bosch Greenstar [5] generating 7 kW_{th} and 1 kW_e. Baxi have the EcoGen [6] a larger unit generating with an auxiliary boiler that generates 24 kW_{th} and 1.1 kW_e. Although it is categorised as a μ-CHP unit, its thermal output is considerably greater than that of the previously mentioned units.

Fuel cell technology is still currently under development although a number of units are at prototype stage and, if successful, fuel cell technology could come to dominate the CHP market. Ceres Power has developed the Solid Oxide Fuel Cell (SOFC) technology so as to be able to operate at temperatures of 500-600°C, substantially lower than conventional designs [7].

The WhisperGen Stirling engine μ-CHP unit was the first commercially-available domestic μ-CHP unit available in the UK, primarily serving the residential market. It is designed to be clean and quite for in-house use and takes up roughly the same space as a standard household appliance [8]. The manufacturer's performance data estimates that the WhisperGen Stirling engine μ-CHP unit delivers an overall operating efficiency of 90% [9].

Given the obvious deployment potential for this unit in the UK residential sector, the Carbon Trust launched the UK's first major field trial (μ-CHP Accelerator study) in 2003 for both domestic and small commercial μ-CHP units. A total of 72 domestic Stirling engine μ-

CHP units were installed and monitored in field trials in typical UK households aimed at a comprehensive performance analysis of μ-CHP units. The majority of the units monitored were WhisperGen Mk ~~4~~IV and Mk ~~5.~~V. Electricity used, gas used, electricity generated, heat generated, case losses and flue losses were measured every 5 minutes with the aim of capturing a full 12 months of continuous operation to take account of seasonal variation in performance. 27 condensing gas boilers were also monitored to provide a relevant baseline against which to compare the performances of the μ-CHP units.

The Carbon Trust final report [10] presented key results from the trial on domestic scale μ-CHP performance and the factors which affect its performance. It reported that, for a dwelling with a typical heat demand of around 20,000 kWh, the absolute annual carbon savings are in the approximate range of 200 to 700 kg per year with an average saving of 400 kg. 50-70% of the electricity generated was exported over the year. On average, the economic benefit of the μ-CHP units was a net annual saving of £158 which results in a simple incremental payback period of just less than 16 years over the condensing gas boiler. The high capital cost of the WhisperGen Stirling engine μ-CHP unit was found to be a deterrent to residential application. For these units to provide primary energy and cost savings relative to conventional boilers, they have to operate for as many hours as possible.

A number of researchers have carried out studies on the energy, economic and environmental performance μ-CHP systems for domestic application. Ren and Gao [11] analysed the performance of two typical μ-CHP units with a gas engine and fuel cell for residential buildings. Two different operating modes including minimum-cost operation and minimum-emission operation were taken into consideration by employing a plan and evaluation model for residential μ-CHP systems. Possidente et al. [12] carried out a comparative energy, economic and environmental performance analysis of three different μ-CHP prototypes against a conventional heating system. TeymouriHamzehkolaei and Sattari [13] carried out a technical and economic feasibility study of using μ-CHP in different climatic zones in Iran. Dorer and Weber [14] compared the energy and environmental performance of a number of μ-CHP systems against traditional condensing gas boiler and heat pump technologies using different building types, occupant related loads and grid electricity mixes.

De Paepe et al. [15] analysed the operational parameters of five μ-CHP systems with capacities less than 5 kW for residential use. Two houses (detached and terraced) were compared with a two storey apartment. Using a dynamic simulation and data from commercially available Stirling engines and a fuel cell, they compared the five μ-CHP systems to separate energy systems consisting of a natural gas boiler and buying electricity from the grid. Their study showed that if the μ-CHP systems are well sized, they would result in a reduction of primary energy use, though different technologies have very different impacts. Their results showed that gas engines seem to have the best performance. An economic analysis showed that fuel cells were still too expensive and even gas engines have a small internal rate of return (<5%) which occurs in favourable economic circumstances.

Alanne et al. [16] explored optimized strategies for integrating Stirling engine-based residential μ-CHP systems based on their performance assessment with focus on time-dependent changes in the energy generation mix and utilizing thermal exhaust through heat recovery to pre-heat supply air. Peacock and Newborough [17] considered the relationship between heat-saving and μ-CHP technological interventions for reducing the carbon footprint of existing domestic dwellings within the UK housing stock. Field tests with several thousand PEM fuel cells for μ-CHP were conducted in Japan by Kimura [18].

Barbieri et al. [19] evaluated the feasibility of μ-CHP systems based on internal combustion engines, micro gas turbines, micro Rankine cycles, Stirling engines and thermophotovoltaic generators to meet the energy demands of two single-family dwellings, and the maximum cost allowed for each system. Their energy performance analysis showed that the μ-CHP units usually satisfy at least 80% of the thermal energy demand, while the ratio between the produced and required electric energy usually remained lower than 85%. Their economic analyses highlighted that a reasonable target for the marginal cost of a CHP system for household heating is approximately 3,000 €/kW_e with the Stirling engine having the best performance under different scenarios. They recommended that the highest profitability can be obtained by sizing the prime mover such that its electric power output should be closest to that of the peak electric demand.

Bianchi et al. [20] analysed the energy benefits and profitability of μ-CHP systems in meeting energy demands in domestic dwellings. Their analysis of the energy performance showed that a μ-CHP unit with appropriately sized thermal storage system can cover the overall thermal energy demand of a building while saving 15-45% of primary energy depending on the technology considered. Their results revealed that proper system sizing of the prime mover and thermal storage, together with large on-site consumption of the electricity produced are key factors that affect the economic viability of the systems. They reported that under the above mentioned conditions, single family houses can allow CHP systems up to 5 kWe, with marginal cost that, in the best scenario, range between 2,000 and 3500 €/kWe.

This paper uses field trial data to evaluate the energy, economic and GHG emission reduction potential of installing a μ-CHP unit in a domestic dwelling in the Republic of Ireland. Because of its commercial availability at the time of the study, a Whispergen Mk 4IV Stirling engine μ-CHP unit was analysed. Monthly energy input and output parameters are presented and analysed and then aggregated to give annual values which are compared against the economic performance and GHG emissions of a conventional domestic condensing gas boiler. Current capital and energy costs in the Republic of Ireland were used is in the economic analysis.

Section 2 of this paper describes the μ-CHP unit and its characteristics while the parameters used to evaluate the energy, economic and environmental performances of the μ-CHP unit are presented in Section 3. Section 4 presents a discussion of the results of the μ-

CHP unit's performance analysis and conclusions drawn based on the comparative performance of the µ-CHP unit against a condensing gas boiler are presented in Section 5.

2. System Description and Characteristics

2.1 System Description

An illustration of a typical installation of the WhisperGen Stirling engine µ-CHP unit used in a residential dwelling is shown in Fig. 1. This is the configuration used for the system reported in this paper. The house evaluated in this study is a typical 4 bed semi-detached single family residential dwelling with a floor area of 140 m^2. The dwelling was built in the 1980s from 225 mm hollow block and brick exterior. The dwelling was retrofitted by installing double glazed windows and insulation in the walls and roof, thus increasing its energy efficiency. The dwelling complied with Building Standards in Northern Ireland at the time of construction and had a standard assessment procedure (SAP) rating of 50. SAP is the UK Government's recommended method for measuring the energy rating of residential dwellings. The house had four occupants and the principal heat demand of the dwelling was for space heating and for a constant supply of hot water.

µ-CHP units are designed to operate on the basis of residential demand for heat or electricity. The installation of the µ-CHP unit in this case displaced the need for a conventional boiler. The µ-CHP unit was installed as a heat-led device and thermal output from the µ-CHP unit was fed into the wet system to meet the dwelling's space heating and domestic hot water needs. The heating system had a three-way valve control fitted which closed when the demand for hot water was satisfied, enabling hot water to be supplied for space heating via the radiators. The heat output from the µ-CHP unit was in the form of low pressure hot water delivered at an outlet temperature of 80^{o}C while the return temperature was approximately 60^{o}C depending on the heat emitted by the radiators. The hot water storage tank was not changed during the µ-CHP unit installation and its volume of 150 litres is as when the gas boiler was fitted. The µ-CHP unit did not modulate but was turned off when the water got to the set temperature. Fig. 1 shows the installation arrangements for the WhisperGen µ-CHP unit in the dwelling. The µ-CHP unit's installation is similar to that of a standard boiler and it was integrated into the dwelling's existing electrical and heating system. The existing electrical services were modified to suit the µ-CHP installation.

2.2 µ-CHP Unit

The core technology behind the WhisperGen Stirling engine Mk ~~4~~IV µ-CHP unit is an external combustion engine. It is a four cylinder double acting Stirling engine and the heat to the engine is provided by a burner situated on top of the cylinders. The Stirling engine operates on the principle that heated gas expands and cooled gas contracts. A burning flow of fuel and air is used to heat nitrogen gas within the 4 cylinders. The heated nitrogen gas expands in the top heat exchanger and then moves to the lower, water cooled part of the cylinder where it contracts. The cooling water removes heat from the cylinders, and the heat thus gained is used for domestic water heating. The cooled nitrogen gas returns to the top heat exchanger and the process is repeated. This rapid heating and cooling leading to the expansion and contraction of the nitrogen gas causes the pistons within the cylinders to move, the up and down motion is connected to a rotary generator by a 'wobble yoke' mechanism [8]. The Stirling engine operates in a very clean and quiet manner since it has no valves and no air or fuel is taken into or out of the cylinder. Table 1 shows the technical specifications of the µ-CHP unit.

Table 1: Technical specifications of the μ-CHP unit [21]

Parameters	Unit	Values
Model		Mk ~~4~~IV AC gas fired
Engine cycle		4 cylinder double acting Stirling
Main burner		Premix surface burner
Maximum heat output	kW	8
Nominal mode	kW	up to 7
Duty cycle		1 – 24 hour cycle
Max installation weight	kg	137
Dimensions (~~wxdxh~~HxWxD)	mm	~~276~~840 x ~~376~~490 x ~~262~~560
Fuel		Natural gas
Gas supply pipe size	mm	22
Fuel consumption	m^3/h	Maximum burner firing rate 1.55
Seasonal efficiency	%	80-90
Electrical supply	V/Hz	230/50 (Nominal grid voltage)
Electrical Output		Up to 1000 Watts AC at 220-240V
Grid connection		4 pole induction generator
Enclosure		Floor mounted, free standing
Connections		Standard pluming connections

2.3 Condensing Gas Boiler

The condensing gas boiler used in this study is a Vokera Mynute HE high efficiency system boiler which has a Passive Flue Gas Heat Recovery (PFGHR) device fitted. This type of boiler is replicated within the Republic of Ireland's housing stock. The post heat exchanger device is located between the boiler and the flue terminal. The device offers the potential to increase efficiency by capturing some of the heat in the boiler flue gases that would normally be wasted. It uses this extracted heat to reduce the amount of fuel that has to be burned when providing hot water. Table 2 shows the technical specifications of the Vokera Mynute HE condensing gas boiler. The performance of the boiler was not metered during the field trial but the recommended baseline seasonal efficiency was used in Eq. 13.

Table 2: Technical specifications of the condensing gas boiler [22]

Controls	Unit	Value
On/Off switch with reset		Yes
User adjustable CH temperature		Yes
Heat input	kW	15
Maximum heat output (80/60°C)	kW	14.81
Maximum heat output (50/30°C)	kW	15.9
Main burner		Premix burner
Max installation weight	kg	38
Dimensions (hxwxdHxWxD)	mm	276 x 376 x 262
Fuel		Natural gas
Gas supply pipe size	mm	22
SEDBUK (2005) Rating (Band)		A
Fuel consumption	m^3/h	1.6
Seasonal efficiency	%	90.4
Electrical supply	V/Hz	230/50
Power Consumption	W	50
Mounting plates		Brackets
CH flow and return pipe size	mm	22

3. μ-CHP Performance Evaluation

The evaluation of the performance of the WhisperGen Stirling engine μ-CHP unit for use in residential application was conducted and parameters analysed using measured data consist of: energy performance; electrical and thermal energy; overall efficiency; and heat to power ratio (HPR).

The 12-month field trial involved the installation of temporary data logging equipment to gather μ-CHP performance data (fuel consumption, heat generated, electricity generated,) and dwelling energy demand profiles (electricity used on-site, electricity exported, electricity imported). Thermal energy output was measured using a heat meter and the electricity demands (import/export) and electrical energy generation were monitored through a mains utility meter. The quantities of gas used were measured in cubic meters using a smart gas meter., A conversion factor of 11.4 was used to convert cubic meters into the corresponding energy (Q_f) in kWh. The WhisperGen manufacturer uses gross or higher calorific value (GCV),

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when stating the efficiency of their μ-CHP. All gas was purchased on the basis of its higher calorific value. The number for higher caloric value of the gas was 38.0 MJ/m^3 and this value was obtained from the gas retailer Phoenix natural gas Northern Ireland.

All performance and demand data were recorded at 30 minute intervals and compiled into daily, weekly, monthly and yearly parameters and used to determine the μ-CHP's performance. The variables recorded during the field trial provide a comprehensive description of the WhisperGen Stirling engine μ-CHP technology under realistic operating conditions.

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3.1 μ-CHP Energy Performance

During operation, for a given quantity of gas used, the μ-CHP unit generates both heat and electrical energy while incurring some energy losses. This is expressed mathematically as:

$$Q_f = Q_h + E_{el} + E_{loss} \quad (1)$$

3.1.1 μ-CHP System Efficiency

There are three different system efficiencies that are important in measuring the performance of μ-CHP systems: the system thermal efficiency, the system electrical efficiency and the system overall efficiency which explain how much and why the energy (in the form of combustible fuel) being supplied to the system is lost [23].

The μ-CHP unit's thermal efficiency is the ratio of total thermal energy output (in the form of heat) produced to the total fuel (higher calorific value, HCV) energy supplied to the system. This relationship is described in Eq. 2 as [23]:

$$\eta_{th,\mu\text{-chp}} = \frac{Q_h}{Q_f} \quad (2)$$

The μ-CHP unit's electrical efficiency is the ratio of total electrical energy output produced to the total fuel energy (HCV) supplied to the system. This relationship is described in Eq. 3 as [23]:

$$\eta_{el} = \frac{E_{el}}{Q_f} \tag{3}$$

The µ-CHP unit's overall efficiency is the ratio of total electrical and thermal energy produced to the total fuel energy (HCV) supplied to the system. This value is found by adding the electrical efficiency and the thermal efficiency and is described in Eq. 4 as [23]:

$$\eta_{overall} = \frac{E_{el} + Q_h}{Q_f} = \eta_{el} + \eta_{th,\mu\text{-}chp} \tag{4}$$

3.3 Economic Analysis

The economic analysis involved comparing the performance of the WhisperGen µ-CHP unit against that of a condensing gas boiler retrofitted in a domestic dwelling. It was assumed that a consumer would choose a gas boiler or a µ-CHP given the former is the lowest cost technology for conveniently producing heat where a natural gas supply exists. The performance characteristics were evaluated to undertake a cost-benefit analysis of each heating system.

In analysing the economic performance of the µ-CHP unit in the dwelling, it was considered that the grid would meet the top-up electrical energy demand or supply the whole electrical demand if the µ-CHP were not running; while for the condensing gas boiler solution, all electricity used in the dwelling is imported from the grid.

Two key parameters used to determine the economic benefits of the µ-CHP unit were gas and electricity tariffs [11]. In the Republic of Ireland, the largest energy retailers providing gas and electricity are Bord Gáis and Electricity Supply Board (ESB) Electric Ireland respectively. For this evaluation and to simplify the costing the standard gas and electricity tariff for 2011 in Ireland were used. Table 3 shows the parameters used in the economic analysis. The export tariff paid by electricity retailers for electricity from the first 3,000 kWh of microgeneration units in the Republic of Ireland is 19 c/kWh [9]. Table 4 shows the heating system parameters. For fully pumped hot water based gas-fired central heating systems, the boiler seasonal efficiency is required to be greater than 86% [24, 25].

Table 3: Parameters used in economic analysis

Parameter	Unit	Value
Grid Electricity Cost $_{(2011)}$	c/kWh	14*
Electricity Export price $_{(2011)}$	c/kWh	19+
Discount Rate	%	10
System Life	Years	15[1]

*Electricity Supply Board Electric Ireland [26]

+Sustainable Energy Authority of Ireland [27]

[1]From manufacturer's data

Table 4: Heating system Parameters

Parameter	Unit	Value
Boiler efficiency (HCV)	%	86.0*
Gross efficiency of μ-CHP	%	84.4+
μ-CHP Electrical efficiency	%	7.9+
μ-CHP thermal efficiency	%	76.5+
Maintenance cost of μ-CHP	c/kWh	0.9[2]
Maintenance cost of condensing gas boiler	c/kWh	0.4[2]
Gas cost	c/kWh	3.9[1]
Condensing gas boiler capital cost	€	1,200[4]
μ-CHP capital cost	€	3,500[4]
Boiler installation cost	€	400[3]
μ-CHP installation cost	€	600[3]
Condensing gas boiler annual maintenance cost	€	90[5]
μ-CHP annual maintenance cost	€	120[6]

*Recommended seasonal baseline efficiency [24, 25]
+Measured from the field trial
[1]Gas tariff [28]
[2]Calculated values from Eqs. 7 and 11
[3]Obtained from suppliers
[4]Obtained from manufacturers
[5]Bord Gáis Energy
[6]Obtained from supplier

The economic analysis considered the following parameters: installation capital cost, annual fuel costs, annual maintenance cost, imported electricity cost, exported electricity revenue generated to provide an overall net cost saving compared to a condensing gas boiler. The unit was considered to have a negligible salvage value and disposal cost, particularly when discounted over its lifespan, so this was ignored. These parameters are calculated using Eqs. 5-11 and the parameters listed in Table 3.

3.3.1 Incremental Payback

The incremental payback is the time period to recover the extra investment of purchasing the μ-CHP unit over the condensing gas boiler. It is calculated using Eq. 5 given as [29]:

$$IPB = \frac{C_{\mu\text{-chp}} - C_{boiler}}{\Delta AS} \quad (5)$$

3.3.2 μ-CHP Unit Operating Cost

The total operating cost of the μ-CHP unit is calculated as the sum of the fuel cost, maintenance cost and the cost of importing electricity, less the cost of displaced electricity imported from the grid and the revenue accrued from electricity exported to the grid. This is represented mathematically as:

$$C_{\mu\text{-chp}} = C_{\mu\text{-chp,f}} + C_{\mu\text{-chp,m}} + E_{imp}T_{imp} - E_{on}T_{imp} - E_{exp}T_{exp}$$

$$C_{\mu\text{-chp}} = C_{\mu\text{-chp,f}} + C_{\mu\text{-chp,m}} + E_{imp}T_{imp} - E_{exp}T_{exp} \quad (6)$$

Field Code Changed

The μ-CHP maintenance cost is calculated using Eq. 7 given as:

$$C_{\mu\text{-chp,m}} = Q_h T_{\mu\text{-chp,m}} \quad (7)$$

The cost of fuel consumed by the μ-CHP unit is calculated using Eq. 8 given as:

$$C_{\mu\text{-chp,f}} = \frac{100 \cdot Q_h T_g}{\eta_{th,\mu\text{-chp}}} \quad (8)$$

3.3.3 Condensing Boiler Operating Cost

The total operating cost of the boiler is calculated as the sum of the fuel cost, maintenance cost and the cost of importing electricity from the grid. It is represented mathematically as:

$$C_{boiler} = C_{bf} + C_{mb} + E_{imp} T_{imp} \tag{9}$$

The cost of fuel consumed by the condensing gas boiler is calculated using Eq. 10 given as:

$$C_{bf} = \frac{100 \cdot Q_{hb} T_{g}}{\eta_{b}} \tag{10}$$

The boiler maintenance cost is calculated using Eq. 11 given as:

$$C_{mb} = Q_{hb} T_{bm} \tag{11}$$

3.4 GHG Emission Analysis

The GHG emission analysis estimates the quantity of CO_2 emissions avoided by the μ-CHP unit compared to the condensing gas boiler, assuming a greater overall efficiency for the former (which generates both heat and electricity) compared to the latter (which generates heat only). The electricity generated by the μ-CHP unit is considered to ~~be CO_2 neutral since the emissions are been accounted for heat~~ displace grid supplied electricity thereby resulting in a reduction in generation~~.~~ from centralised power plants. Therefore, both the ~~1385~~1,383 kWh of electricity consumed on-site and the 680 kWh of electricity exported were considered to ~~have no impact on CO_2 emission calculations. This assumption is valid for limited deployment of~~reduce CO_2 emissions from the house fitted with the ~~technology which would have little impact on the production of electricity in centralised power plants. However, if a large number of μ~~μ-CHP ~~units were deployed in a controlled manner, then this would result in a reduction in the overall production of electricity in centralised power plants, therefore yielding a reduction of CO_2 emissions~~unit.

The GHG emission analysis therefore consists of evaluating the performance of the μ-CHP unit using CO_2 emissions savings relative to the condensing gas boiler fitted in the house. This requires us to evaluate the emissions associated to a house fitted with a condensing gas boiler. These emissions are due to heat generated by the gas boiler and electricity imported from the grid. On the other hand, emissions associated to a house fitted with a μ-CHP unit are due to imported grid electricity and the heat generated by the unit. μ-CHP electricity generated was assumed to be CO_2 free or neutral (all emissions were attributed to heat production with electricity output viewed as a 'by-product'). less emissions due to electricity generated. The base year (2011) CO_2 intensities of grid supplied electricity and natural gas in Ireland were 0.504 kgCO_2/kWh [28] and 0.18 kgCO_2/kWh [30] respectively.

3.4.1 μ-CHP

In a house fitted with a μ-CHP unit, the total quantity of emitted CO_2 is the sum of the CO_2 associated with electricity imported from the grid and the quantity of CO_2 associated with heat generated minus the amountquantity of avoided CO_2 emissions associated with electricity generated by the μ-CHP unit that is used on-site. and/or exported to the grid. This is expressed as:

$$EC_{\mu-chp} = E_{imp}CI_{ge} + \frac{100 \cdot Q_h CI_{ng}}{\eta_{th,\mu-chp}} - E_{on}CI_{ge} \quad EC_{\mu-chp} = E_{imp}CI_{ge} + \frac{100 \cdot Q_h CI_{ng}}{\eta_{th,\mu-chp}} - (E_{on} + E_{Exp})CI_{ge}$$

(12)

Field Code Changed

3.4.2 Condensing Gas Boiler

In a house fitted with a condensing gas boiler, the amount of CO_2 emitted is the sum of emissions due to electricity imported from the grid and heat generated by the boiler. This is expressed as:

$$EC_b = E_d CI_{ge} + \frac{100 \cdot Q_{hb} CI_{ng}}{\eta_{th,b}} \tag{13}$$

4 Results and Discussion

4.1 Energy Analysis

Fig. 2 shows an energy balance diagram for the μ-CHP unit which summarises the results of the data obtained from the field trial. It can be seen from the figure that for a given quantity of gas used by the μ-CHP unit, on average 76.5% is converted into heat, 7.9% into electricity while losses account for 15.6%.

4.1.1 Heat and Electricity Demand

The energy demand of the dwelling can be divided into heat and electricity. The dwelling had an annual heat and electrical energy demand of 20,095 kWh and 6,663 kWh respectively. Fig. 3 shows the monthly total electrical and heat energy use of the dwelling during the field trial period. The maximum monthly heat and electrical energy consumption were 3,138 kWh in January 2005 and 667 kWh in December 2004 while the corresponding minimum values were 531 kWh in August 2004 and 470 kWh in June 2005. The electrical energy use did not vary much throughout the year while the heat energy demand was highest during the winter months (hot water and space heating) and relatively constant during the summer months (hot water only). The electrical energy consumption varied seasonally but the average electrical energy demand during the summer months was 500 kWh, while for the winter months it was 606 kWh. Heat use also varied seasonally with average values of 761 kWh during the summer months and 2,870 kWh during the winter months.

4.1.2 Heat and Electricity Generated

The µ-CHP unit operated reliably achieving an availability of 97%. The 3% downtime was as a result of technical difficulties and teething problems associated with the infancy of the µ-CHP unit. Monthly demand profiles were used to determine the amounts of heat and electricity required by the dwelling. Fig. 4 shows variations in the monthly heat and electrical energy generated by µ-CHP unit during the field trial period. During the field trial period, the µ-CHP generated 2,063 kWh_e and 20,095 kWh_{th} of electricity and heat respectively. The maximum heat and electrical energy generated were 3,138 kWh and 337 kWh respectively in January 2005. The minimum heat generated was 531 kWh in August 2004 while the minimum electricity generated was 49 kWh in August 2004 and June 2005.

4.1.3 Electrical Energy Balance

Electricity output from a heat-led µ-CHP unit is determined by the household's heat demand that varies considerably depending on the building type, building standard, location of the house and occupant behaviour [31]. Fig. 5 shows monthly plots of electricity generated, exported and total electricity used on-site during the field trial period. The electrical energy generated and used on-site varied seasonally but the average monthly figure during the summer months was 52 kWh, while it was 296 kWh during the winter months. The µ-CHP unit provided 20.8% of the dwelling's electrical requirement on an annual basis.

Of the 2,063 kWh of electricity generated by the µ-CHP unit during the year, 1,383 kWh was used on-site while 680 kWh was exported to the grid. 5,280 kWh therefore had to be imported to meet the electricity demand of the dwelling.

As expected, the greatest amount of electricity exported was for the period October 04 to April 05. This was partially due to the unit being signalled to start up early morning to meet the required room temperature when the household's electricity demand was low. The maximum electricity exported was 101 kWh in January 05 while the minimum electricity exported was 18 kWh in August 04. The maximum amount of electricity imported was 519 kWh in October 04 while the minimum amount electricity imported was 321 kWh in February 05.

4.1.4 System Efficiencies

Calculations of energy efficiency were carried using metered fuel input, electrical output and heat output. Fig. 6 shows the µ-CHP unit's efficiencies during selected days for each month of the monitoring period. The electrical efficiency varied from 6.1% to 9.1% but the average annual efficiency was 7.9%. The low electrical efficiency of the µ-CHP unit reflects its high heat to power ratio (HPR) which varied from 9.1 to 12.7 over the period. A maximum value of overall efficiency of 92.2% was recorded with an average value of 86.3% calculated for the whole year.

4.2 Economic Analysis

A detailed financial appraisal was carried out to assess the economic viability of the µ-CHP unit, given that its capital and initial installation costs are considerably higher than those for a condensing gas boiler. The financial performances of the condensing gas boiler and the µ-CHP unit were evaluated over their life cycle. The economics of the µ-CHP unit is dominated by natural gas fuel (the main running cost) as well as imported and displaced electricity costs. Periodic maintenance represents another operating cost. The maintenance requirements for µ-CHP units are always higher compared to conventional gas boilers. However, some µ-CHP units (e.g. Stirling engines units) are approaching the low maintenance requirements of conventional gas boilers.

The economics of the heating system with the µ-CHP unit is highly dependent on the magnitude of residential energy consumption, especially the thermal energy demand [11, 32] since this dictates the µ-CHP assets' utilisation rate and payback periods. As was expected the annual fuel costs of the condensing gas boiler was lower than that of the µ-CHP unit due to its higher thermal efficiency which leads to lower fuel consumption. The dwelling fitted with a condensing gas boiler however has a higher cost of imported electricity than that for the µ-CHP unit since the boiler does not produce any electricity. The values of exported and displaced electricity are therefore important factors in the economic performance of the µ-CHP unit. The µ-CHP unit was found to have a lower net annual operating cost compared to the condensing gas boiler.

4.2.1 Monthly Operational Cost Savings

The monthly cost savings (€/month) for the existing dwelling are based on the gas and electricity prices in the Republic of Ireland given in Table 5. Fig. 7 shows the monthly operational cost savings achieved by the µ-CHP unit during the field trial. Moran et al. [23] reported that at certain fuel and electricity prices, µ-CHP systems can produce noticeable savings in monthly energy costs. The factors which made these savings possible were the cost of gas, their high generating efficiency and the high availability of the unit. The distribution of savings is shown in Fig. 7 which shows that the highest monthly saving was in January 2005 at €37.60 and lowest in August 2004 at €0.50. The average monthly operating saving was €15.00.

4.2.2 Annual Operational Cost Savings

The annual cost savings achieved by the µ-CHP unit was €180. The incremental cost of the µ-CHP unit was €2,500 more than a condensing gas boiler. This therefore requires a simple, undiscounted payback period of 13.8 years to recover the additional investment.

Table 5 shows a summary of the results of the comparative economic appraisal of the µ-CHP unit against the condensing gas boiler. The electricity consumed by the condensing gas boiler and µ-CHP unit circulation pumps was considered to be negligible and is therefore not included in the analysis. For the µ-CHP unit the sum of maintenance, fuel and electricity costs add up to a total operating cost of €1,883. If we include the revenue of €129 from exported electricity, this would result in a total operating cost of 1,754.

Over a 15 year operating period and a discount rate of 10% [33], assuming no escalation in maintenance cost, electricity and gas prices, the net present value (NPV) for the condensing gas boiler and μ-CHP units were -€16,310 and -€15,965 respectively. The higher NPV of the μ-CHP unit shows that it is economically better to invest in the μ-CHP unit rather than the condensing gas boiler. The Carbon Trust field trial [10] showed an economic benefit of £158 annually (€180 in the Republic of Ireland) and simple incremental payback period of 16 years (13.8 years in Ireland) over the condensing gas boiler.

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Table ~~3~~5: Summary of result

Description	Condensing gas boiler	μ-CHP
Revenue		
Exported electricity (€)	0	129
Costs		
Annual maintenance (€)	90	120
Annual fuel (€)	911	1,024
Imported electricity (€)	933	739
Annual total operating (€)	1,934	1,754
Annual saving (€)	0	180
Incremental capital (€)*	0	2,500
Economic appraisal		
Incremental payback period (years)	0	13.8
Net present value (€)	-16,310	-15,965

*This is the difference between the capital cost of the μ-CHP unit and the condensing gas boiler.

4.3 GHG Emission Analysis

CO_2 emissions reduction is the primary environmental advantage of the μ-CHP. The measured carbon savings of the μ-CHP are benchmarked against a condensing gas boiler and grid supplied electricity.

Table 6 shows CO_2 emissions for a house fitted with a conventional gas boiler and a μ-CHP unit. The total CO_2 emissions for the μ-CHP unit and condensing gas boiler were calculated using Eqs. 12 and 13 respectively. The quantity of CO_2 emissions of heat generated were calculated using the amount of gas consumed by the μ-CHP unit and condensing gas boiler taking into account their thermal efficiencies.~~ It is seen that the CO_2 emissions of imported electricity from the grid for a condensing gas boiler are 697 KgCO_2 per annum greater than those of the μ-CHP. Total emissions avoided by the μ-CHP generated electricity were 1,039 KgCO_2 per annum. The 1,039 KgCO_2 per annum includes 343 KgCO_2 per annum of exported electricity which was generated on site and is considered CO_2 neutral. The CO_2 emissions due to importing electricity from the grid is 21% greater for a house fitted with a condensing gas boiler than for the same house fitted with a μ-CHP unit. CO_2 emissions associated with heat generated by the condensing gas boiler are 523 KgCO_2 per annum or 11% lower due to condensing gas boiler's higher heat generation efficiency.~~

The data shown in Table 6 are in line with the manufacturer's predictions of the environmental advantage of avoided CO_2 emissions associated with the μ-CHP. Overall, the dwelling fitted with a μ-CHP system and topping up its electricity needs from the grid generated 2,063 kWh of electricity. This resulted in emissions savings of ~~174~~1,040 kgCO_2 per annum (~~2.3~~16.1%) less than one fitted with a condensing gas boiler and importing all its electricity needs. Taking the results in Table 6 over the estimated lifespan of 15 years, assuming no changes in efficiency and no further reduction in CO_2 intensity of grid supplied electricity the μ-CHP unit would save ~~2~~15.6 tCO_2. ~~This finding is supported by results~~The findings of this study are an improvement of those of the field trial runs by the Carbon Trust [10] which found that at the current stage of μ-CHP technology development, limited contributions to CO_2 reduction can be achieved. ~~While the μ-CHP unit had net average annual carbon~~ The limited CO_2 emission savings ~~of 400 kgCO_2 per annum in the UK, the unit resulted in 174 kgCO_2 per annum average savings in the Republic of Ireland. This was~~ by the Carbon

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Trust study is as a result of ~~the lower carbon intensity of grid~~ their assumption that the electricity ~~and natural gas in Ireland (0.504 $kgCO_2$ and 0.180 $kgCO_2$) compared to that in the UK (0.568 $kgCO_2$ and 0.225 $kgCO_2$) used in the analyses. The Carbon Trust~~ generated by the μ-CHP unit was carbon neutral. They therefore recommended that considerable improvements in the technology ~~are~~would be required~~. Use~~ and that the use of the μ-CHP unit would ~~therefore~~ make sense in countries/regions with high emissions intensity of electricity production. Our findings therefore reveal that the WhisperGen Mk IV Stirling engine μ-CHP unit has the capacity to generate electricity in the home and contribute positively to the concept of distributed power generation while reducing CO_2 emissions.

It is interesting to note that both Ireland and the UK are currently engaged in the construction of considerable quantities of renewable energy (mainly wind) which will result in the further decarbonisation of the electricity system. If for example, the emissions intensity of electricity were to fall to 0.4 $kgCO_2$ then emissions savings from the μ-CHP with grid top-up will decrease to ~~31~~855 $kgCO_2$ per annum or ~~0.5~~12.4% over the boiler with grid import electricity.

Table 6: CO_2 emissions for a house with a conventional boiler and μ-CHP unit

Parameters	Condensing gas boiler ($kgCO_2$/pa)	μ-CHP ($kgCO_2$/pa)
CO_2 emissions of imported electricity	3,358	2,661
CO_2 emissions of heat generated	4,205	4,728
Avoided emissions due to reduction of electricity production in power plant	-	-1,040
Total CO_2 emissions	7,563	~~7,389~~6,349
Avoided emissions due to μ-CHP		-~~174~~1,214
~~%~~Percentage of avoided emissions (%)		~~2.3~~16.1

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5. Conclusions

The core question investigated in this paper is the extent to which μ-CHP can reduce life cycle costs, emissions and energy requirements in a domestic dwelling in Ireland and the extent of its attractiveness to domestic homeowners, energy suppliers and policy makers.

Operating a WhisperGen Mk IV Stirling engine μ-CHP unit in the house studied resulted in primary energy savings compared to a standard condensing gas boiler. It resulted in an energy saving of 2,063 kWh of electricity and generated a thermal output of 20,095 kWh during the field trial period, operated for 2,512 hrs and generated an annual cost saving of €180. This resulted in an incremental simple payback period of 13.8 year over the condensing gas boiler. The μ-CHP unit used 2,889 kWh of gas more than the condensing gas boiler. It reduced the quantity of imported electricity by 20.8%. A major achievement was the reliability of the μ-CHP unit, which achieved an availability of 97% for the year.

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The monthly overall efficiency fluctuated from 78.6% in August 2004 to a maximum value of 92.3% in December 2004 with a yearly average operating overall efficiency of 86.3%. The heat outputs measured during the field trial were similar to those quoted by the manufacturer generating a maximum heat output of 8.4 kW.

While the economic performance appears attractive, the disadvantage of the WhisperGen Mk IV Stirling engine μ-CHP unit is its high capital cost, a deterrent to purchasers. In order to achieve a reasonably low incremental payback period of say 5 years, the additional cost of the μ-CHP unit over the condensing gas boiler should be no more than €900.

CO_2 emissions reduction was the primary environmental advantage of the μ-CHP specified by the manufacturer and cited in literature ~~but this~~. The analysis in this study showed that there was a decrease of ~~174~~1,040 kgCO_2 per annum from the fossil fuel driven μ-CHP unit compared to a condensing gas boiler fitted in the house. Given its sensitivity to the CO_2 emissions intensity of grid electricity and the on-going decarbonisation of the electrical generation systems both in Ireland and the UK, very significant performance improvements will be needed for this technology to compete as an environmentally-friendly alternative to conventional energy technologies.

The Whispergen Mk IV μ-CHP unit was a prototype, based on Stirling engine technology. The concept was to generate 8 kW of heat and 1 kW of electricity for application in the domestic sector. The purpose of the field trial from June 2004 to July 2005 was to evaluate the economic, energy and emission performance of the prototype Whispergen Mk IV μ-CHP unit installed in a dwelling with a hydronic heating system and assess the feasibility of this prototype technology as a competitive alternative to a condensing gas boiler fitted in a house. The Whispergen Mk IV μ-CHP unit's main advantage compared to a conventional condensing gas boiler is that it produces 1 kW of electrical power. This information is very valuable for researchers, policy makers, academics and the wider scientific community. The Whispergen Mk IV μ-CHP unit is no longer state-of-the-art and is superseded by the Whispergen Mk V unit, incorporating a supplementary burner. It was introduced in 2006 to provide additional flexibility, making the unit suitable for larger dwellings. The Whispergen Mk IV μ-CHP unit is a compact product, very reliable and was in development for 15 years.

The Whispergen Mk V μ-CHP unit delivers a thermal output of 7 kW_{th} (engine) plus 5kW_{th} (burner) installed into the hydronic heating system fitted with a 300 litre storage tank nowadays. Because of the greater thermal output and larger storage capacity, this unit is achieving even higher annual savings and greater reduction in CO_2 emissions.

Acknowledgements

The authors would like to thank Gwyneth Scott of Northern Ireland Electricity for the data used in the analyses in this paper and Phoenix Gas, Northern Ireland.

Nomenclature

C_{boiler}	total operating cost of boiler (€)
C_{bf}	boiler fuel cost (€)
$C_{\mu\text{-}chp}$	total operating cost of μ-CHP unit (€)
$C_{\mu\text{-}chp,f}$	μ-CHP fuel cost (€)
$C_{\mu\text{-}chp,m}$	μ-CHP maintenance cost (€)
C_{mb}	total boiler maintenance cost (€)
CI_{ge}	the carbon intensity of grid electricity ($kgCO_2$/kWh/Pa)
CI_{ng}	carbon intensity of natural gas ($kgCO_2$/kWh)
CI_b	carbon intensity of conventional boiler ($kgCO_2$)
E_d	the total electricity demand (kWh)
E_{el}	electrical energy generated (kWh)
E_{exp}	electricity generated by μ-CHP exported to grid (kWh)
E_{imp}	electricity imported from the grid (kWh)
E_{loss}	energy losses (kWh)
E_{on}	electricity generated by μ-CHP used on-site (kWh)
EC_b	emitted carbon associated with electricity imported from the grid ($kgCO_2$/Pa)
$EC_{\mu\text{-}CHP}$	emitted carbon associated with electricity imported from the grid ($kgCO_2$/Pa)
IPB	incremental payback period (years)
kW_e	kilowatt hour of electricity
kW_{th}	kilowatt hour of heat
Q_h	quantity of heat generated by μ-CHP (kWh)
Q_{hb}	quantity of heat generated by the boiler (kWh)
Q_f	quantity of fuel used (kWh)
T_{imp}	tariff of imported electricity (€/kWh)
T_{exp}	tariff of exported electricity (€/kWh)
T_{bm}	tariff of unit boiler maintenance (€/kWh)
T_g	gas tariff (€/kWh)
$T_{\mu\text{-}chp,m}$	tariff of μ-CHP maintenance (€/kWh_{th})
ΔAS	incremental annual saving (€/year)
η_{el}	electrical efficiency (%)
$\eta_{overall}$	overall efficiency of the μ-CHP unit (%)
$\eta_{th,b}$	thermal efficiency of condensing gas boiler (%)
$\eta_{th,\mu\text{-}chp}$	thermal efficiency of μ-CHP unit(%)

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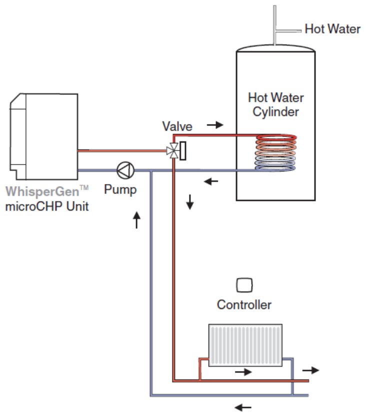

Fig 1. Installation diagram of the WhisperGen Stirling engine μ-CHP unit used in the residential dwelling [18]

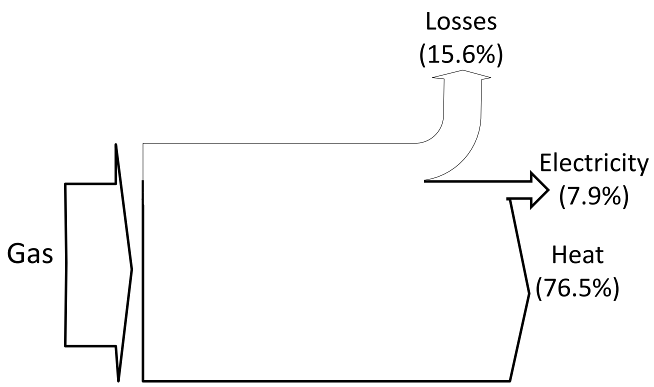

Fig. 2. Energy balance diagram for the μ-CHP unit

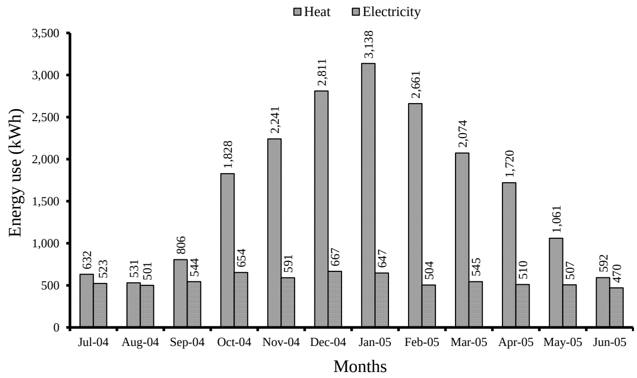

Fig. 3. Heat & electrical energy demand profile for the field trial dwelling over a Year

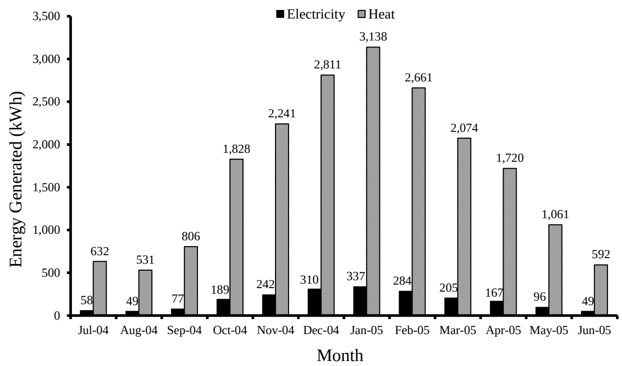

Fig. 4: Total monthly heat and electricity generated by the μ-CHP unit

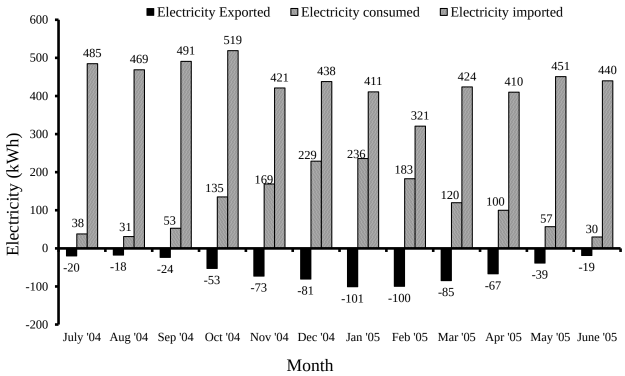

Fig. 5. Electricity imported, exported and total electricity used on site during the field trial period

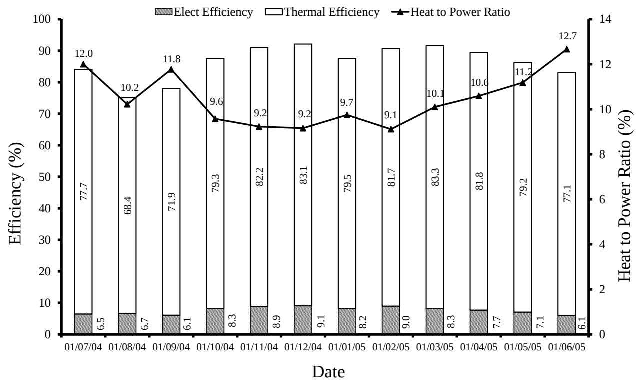

Fig. 6. Efficiencies and HPR for selected days for each month

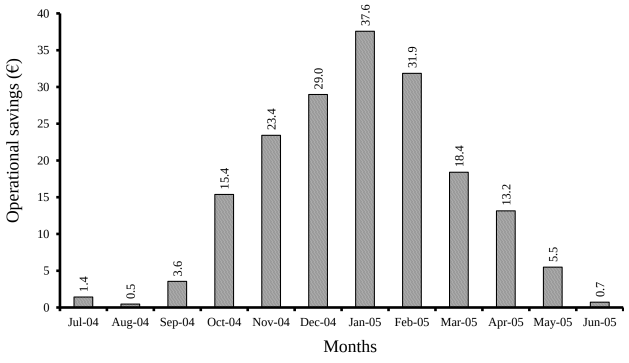

Fig. 7. Monthly cost savings achieved by the μ-CHP unit

Economic, energy and GHG emissions performance evaluation of a Whispergen Mk IV Stirling engine µ-CHP unit in a domestic dwelling

G. Conroy, A. Duffy[1]* and L.M. Ayompe*
School of Civil & Building Services Engineering, Dublin Institute of Technology, Dublin 1, Ireland.
*School of Civil & Building Services Engineering and Dublin Energy Lab, Dublin Institute of Technology, Dublin 1, Ireland.

Abstract

This paper presents an assessment of the energy, economic and greenhouse gas emissions performances of a WhisperGen Mk IV Stirling engine µ-CHP unit for use in a conventional house in the Republic of Ireland. The energy performance data used in this study was obtained from a field trial carried out in Belfast, Northern Ireland during the period June 2004 - July 2005 by Northern Ireland Electricity and Phoenix Gas working in collaboration with Whispertech UK. A comparative performance analysis between the µ-CHP unit and a condensing gas boiler revealed that the µ-CHP unit resulted in an annual cost saving of €180 with an incremental simple payback period of 13.8 years when compared to a condensing gas boiler. Electricity imported from the grid decreased by 20.8% while CO_2 emissions decreased by 16.1%. The µ-CHP unit used 2,889 kWh of gas more than the condensing gas boiler.

Keywords: µ-CHP, Stirling engine, condensing gas boiler, WhisperGen, microgeneration

1. Introduction

One of the greatest challenges mankind faces today is the fight against climate change. Renewable and sustainable energy technologies have the potential to reduce greenhouse gas (GHG) emissions, increase economic competitiveness and enhance security of supply. In

[1] Corresponding author: Email: aidan.duffy@dit.ie
Tel: +353 14023940

Europe, the EU27 member states have committed to an overall 20% reduction in GHG emissions (compared to 1990 levels) and a 20% improvement in energy efficiency by 2020. The residential sector accounted for 26.5% of EU energy requirements in 2009, second only to transport at 33.2%. Direct CO_2 emissions from the sector were 431.9 $MtCO_2$ which accounted for 10.7% of the total CO_2 emissions within the EU [1]; this proportion increases to 20-30% when direct emissions from energy conversion processes (excluding emissions from electricity) are included. This sector therefore has great potential to contribute to the EU's greenhouse gas emissions reduction targets. However, any policy initiatives in the sector require a thorough analysis of the CO_2 emissions reduction potential of different energy efficient and microgeneration technologies such as micro combined heat and power (μ-CHP), fuel cells, solar water heaters, photovoltaic systems and biomass boilers which can supply heat and electricity with reduced CO_2 emissions.

μ-CHP units are localised power generating stations producing both heat and electricity at the point of use and can export excess electricity generated if connected to the national grid. The thermal output is used for hot water and space heating while the AC electricity is used locally in the house or, if demand is sufficiently low, is fed onto the local distribution system. They are especially suited to situations where there is simultaneous heat and power demand as is prevalent in houses in northern European countries. The benefits of μ-CHP units include [2]:

- high overall energy conversion efficiency (in excess of 90% for Stirling engines);
- very low noise and vibration levels; and
- very low emissions of NOx, COx, SOx and particulates.

Typical operating efficiencies for μ-CHP units are between 80 to 90% compared with less than 40% of primary energy input for conventional power generating systems that supply electricity to the grid. CHP technologies fall into three groups: internal combustion engines, external combustion engines (e.g. Stirling cycle) and fuel cells.

There are several manufacturers of combined heat and power (CHP) units in the market and although the technology is developing, there are very few μ-CHP units available to buy. The main suppliers of internal combustion engine CHP units include Baxi Dachs [3] and Honda Ecowill [4]. The Baxi Dachs produces 12 kW of heat and 5 kW of electricity. The Honda Ecowill produces 2.5 kW of heat and 1 kW of electrical power and can only be fitted in parallel with a conventional boiler in a domestic dwelling because of its low energy production capacity. Leading suppliers of external combustion engines include Baxi Dachs, Whispertech and Worcester Bosch. Whispertech (New Zealand) developed the WhisperGen Stirling engine which generates 1 kW of electricity (kW_e) and 8 kW of heat (kW_{th}). Worcester Bosch's unit is the Worcester Bosch Greenstar [5] generating 7 kW_{th} and 1 kW_e. Baxi have the EcoGen [6] a larger unit generating with an auxiliary boiler that generates 24 kW_{th} and 1.1 kW_e. Although it is categorised as a μ-CHP unit, its thermal output is considerably greater than that of the previously mentioned units.

Fuel cell technology is still currently under development although a number of units are at prototype stage and, if successful, fuel cell technology could come to dominate the CHP market. Ceres Power has developed the Solid Oxide Fuel Cell (SOFC) technology so as to be able to operate at temperatures of 500-600°C, substantially lower than conventional designs [7].

The WhisperGen Stirling engine μ-CHP unit was the first commercially-available domestic μ-CHP unit available in the UK, primarily serving the residential market. It is designed to be clean and quite for in-house use and takes up roughly the same space as a standard household appliance [8]. The manufacturer's performance data estimates that the WhisperGen Stirling engine μ-CHP unit delivers an overall operating efficiency of 90% [9].

Given the obvious deployment potential for this unit in the UK residential sector, the Carbon Trust launched the UK's first major field trial (μ-CHP Accelerator study) in 2003 for both domestic and small commercial μ-CHP units. A total of 72 domestic Stirling engine μ-

CHP units were installed and monitored in field trials in typical UK households aimed at a comprehensive performance analysis of μ-CHP units. The majority of the units monitored were WhisperGen Mk IV and Mk V. Electricity used, gas used, electricity generated, heat generated, case losses and flue losses were measured every 5 minutes with the aim of capturing a full 12 months of continuous operation to take account of seasonal variation in performance. 27 condensing gas boilers were also monitored to provide a relevant baseline against which to compare the performances of the μ-CHP units.

The Carbon Trust final report [10] presented key results from the trial on domestic scale μ-CHP performance and the factors which affect its performance. It reported that, for a dwelling with a typical heat demand of around 20,000 kWh, the absolute annual carbon savings are in the approximate range of 200 to 700 kg per year with an average saving of 400 kg. 50-70% of the electricity generated was exported over the year. On average, the economic benefit of the μ-CHP units was a net annual saving of £158 which results in a simple incremental payback period of just less than 16 years over the condensing gas boiler. The high capital cost of the WhisperGen Stirling engine μ-CHP unit was found to be a deterrent to residential application. For these units to provide primary energy and cost savings relative to conventional boilers, they have to operate for as many hours as possible.

A number of researchers have carried out studies on the energy, economic and environmental performance μ-CHP systems for domestic application. Ren and Gao [11] analysed the performance of two typical μ-CHP units with a gas engine and fuel cell for residential buildings. Two different operating modes including minimum-cost operation and minimum-emission operation were taken into consideration by employing a plan and evaluation model for residential μ-CHP systems. Possidente et al. [12] carried out a comparative energy, economic and environmental performance analysis of three different μ-CHP prototypes against a conventional heating system. TeymouriHamzehkolaei and Sattari [13] carried out a technical and economic feasibility study of using μ-CHP in different climatic zones in Iran. Dorer and Weber [14] compared the energy and environmental performance of a number of μ-CHP systems against traditional condensing gas boiler and heat pump technologies using different building types, occupant related loads and grid electricity mixes.

De Paepe et al. [15] analysed the operational parameters of five μ-CHP systems with capacities less than 5 kW for residential use. Two houses (detached and terraced) were compared with a two storey apartment. Using a dynamic simulation and data from commercially available Stirling engines and a fuel cell, they compared the five μ-CHP systems to separate energy systems consisting of a natural gas boiler and buying electricity from the grid. Their study showed that if the μ-CHP systems are well sized, they would result in a reduction of primary energy use, though different technologies have very different impacts. Their results showed that gas engines seem to have the best performance. An economic analysis showed that fuel cells were still too expensive and even gas engines have a small internal rate of return (<5%) which occurs in favourable economic circumstances.

Alanne et al. [16] explored optimized strategies for integrating Stirling engine-based residential μ-CHP systems based on their performance assessment with focus on time-dependent changes in the energy generation mix and utilizing thermal exhaust through heat recovery to pre-heat supply air. Peacock and Newborough [17] considered the relationship between heat-saving and μ-CHP technological interventions for reducing the carbon footprint of existing domestic dwellings within the UK housing stock. Field tests with several thousand PEM fuel cells for μ-CHP were conducted in Japan by Kimura [18].

Barbieri et al. [19] evaluated the feasibility of μ-CHP systems based on internal combustion engines, micro gas turbines, micro Rankine cycles, Stirling engines and thermophotovoltaic generators to meet the energy demands of two single-family dwellings, and the maximum cost allowed for each system. Their energy performance analysis showed that the μ-CHP units usually satisfy at least 80% of the thermal energy demand, while the ratio between the produced and required electric energy usually remained lower than 85%. Their economic analyses highlighted that a reasonable target for the marginal cost of a CHP system for household heating is approximately 3,000 €/kW_e with the Stirling engine having the best performance under different scenarios. They recommended that the highest profitability can be obtained by sizing the prime mover such that its electric power output should be closest to that of the peak electric demand.

Bianchi et al. [20] analysed the energy benefits and profitability of μ-CHP systems in meeting energy demands in domestic dwellings. Their analysis of the energy performance showed that a μ-CHP unit with appropriately sized thermal storage system can cover the overall thermal energy demand of a building while saving 15-45% of primary energy depending on the technology considered. Their results revealed that proper system sizing of the prime mover and thermal storage, together with large on-site consumption of the electricity produced are key factors that affect the economic viability of the systems. They reported that under the above mentioned conditions, single family houses can allow CHP systems up to 5 kWe, with marginal cost that, in the best scenario, range between 2,000 and 3500 €/kWe.

This paper uses field trial data to evaluate the energy, economic and GHG emission reduction potential of installing a μ-CHP unit in a domestic dwelling in the Republic of Ireland. Because of its commercial availability at the time of the study, a Whispergen Mk IV Stirling engine μ-CHP unit was analysed. Monthly energy input and output parameters are presented and analysed and then aggregated to give annual values which are compared against the economic performance and GHG emissions of a conventional domestic condensing gas boiler. Current capital and energy costs in the Republic of Ireland were used is in the economic analysis.

Section 2 of this paper describes the μ-CHP unit and its characteristics while the parameters used to evaluate the energy, economic and environmental performances of the μ-CHP unit are presented in Section 3. Section 4 presents a discussion of the results of the μ-

CHP unit's performance analysis and conclusions drawn based on the comparative performance of the µ-CHP unit against a condensing gas boiler are presented in Section 5.

2. System Description and Characteristics

2.1 System Description

An illustration of a typical installation of the WhisperGen Stirling engine µ-CHP unit used in a residential dwelling is shown in Fig. 1. This is the configuration used for the system reported in this paper. The house evaluated in this study is a typical 4 bed semi-detached single family residential dwelling with a floor area of 140 m^2. The dwelling was built in the 1980s from 225 mm hollow block and brick exterior. The dwelling was retrofitted by installing double glazed windows and insulation in the walls and roof, thus increasing its energy efficiency. The dwelling complied with Building Standards in Northern Ireland at the time of construction and had a standard assessment procedure (SAP) rating of 50. SAP is the UK Government's recommended method for measuring the energy rating of residential dwellings. The house had four occupants and the principal heat demand of the dwelling was for space heating and for a constant supply of hot water.

µ-CHP units are designed to operate on the basis of residential demand for heat or electricity. The installation of the µ-CHP unit in this case displaced the need for a conventional boiler. The µ-CHP unit was installed as a heat-led device and thermal output from the µ-CHP unit was fed into the wet system to meet the dwelling's space heating and domestic hot water needs. The heating system had a three-way valve control fitted which closed when the demand for hot water was satisfied, enabling hot water to be supplied for space heating via the radiators. The heat output from the µ-CHP unit was in the form of low pressure hot water delivered at an outlet temperature of 80^oC while the return temperature was approximately 60^oC depending on the heat emitted by the radiators. The hot water storage tank was not changed during the µ-CHP unit installation and its volume of 150 litres is as when the gas boiler was fitted. The μ-CHP unit did not modulate but was turned off when the water got to the set temperature. Fig. 1 shows the installation arrangements for the WhisperGen μ-CHP unit in the dwelling. The μ-CHP unit's installation is similar to that of a standard boiler and it was integrated into the dwelling's existing electrical and heating system. The existing electrical services were modified to suit the μ-CHP installation.

2.2 μ-CHP Unit

The core technology behind the WhisperGen Stirling engine Mk IV μ-CHP unit is an external combustion engine. It is a four cylinder double acting Stirling engine and the heat to the engine is provided by a burner situated on top of the cylinders. The Stirling engine operates on the principle that heated gas expands and cooled gas contracts. A burning flow of fuel and air is used to heat nitrogen gas within the 4 cylinders. The heated nitrogen gas expands in the top heat exchanger and then moves to the lower, water cooled part of the cylinder where it contracts. The cooling water removes heat from the cylinders, and the heat thus gained is used for domestic water heating. The cooled nitrogen gas returns to the top heat exchanger and the process is repeated. This rapid heating and cooling leading to the expansion and contraction of the nitrogen gas causes the pistons within the cylinders to move, the up and down motion is connected to a rotary generator by a 'wobble yoke' mechanism [8]. The Stirling engine operates in a very clean and quiet manner since it has no valves and no air or fuel is taken into or out of the cylinder. Table 1 shows the technical specifications of the μ-CHP unit.

2.3 Condensing Gas Boiler

The condensing gas boiler used in this study is a Vokera Mynute HE high efficiency system boiler which has a Passive Flue Gas Heat Recovery (PFGHR) device fitted. This type of boiler is replicated within the Republic of Ireland's housing stock. The post heat exchanger device is located between the boiler and the flue terminal. The device offers the potential to increase efficiency by capturing some of the heat in the boiler flue gases that would normally be wasted. It uses this extracted heat to reduce the amount of fuel that has to be burned when providing hot water. Table 2 shows the technical specifications of the Vokera Mynute HE condensing gas boiler. The performance of the boiler was not metered during the field trial but the recommended baseline seasonal efficiency was used in Eq. 13.

3. µ-CHP Performance Evaluation

The evaluation of the performance of the WhisperGen Stirling engine µ-CHP unit for use in residential application was conducted and parameters analysed using measured data consist of: energy performance; electrical and thermal energy; overall efficiency; and heat to power ratio (HPR).

The 12-month field trial involved the installation of temporary data logging equipment to gather µ-CHP performance data (fuel consumption, heat generated, electricity generated,) and dwelling energy demand profiles (electricity used on-site, electricity exported, electricity imported). Thermal energy output was measured using a heat meter and the electricity demands (import/export) and electrical energy generation were monitored through a mains utility meter. The quantities of gas used were measured in cubic meters using a smart gas meter. A conversion factor of 11.4 was used to convert cubic meters into the corresponding energy (Q_f) in kWh. The WhisperGen manufacturer uses gross or higher calorific value (GCV), when stating the efficiency of their µ-CHP**.** All gas was purchased on the basis of its higher calorific value. The number for higher caloric value of the gas was 38.0 MJ/m^3 and this value was obtained from the gas retailer Phoenix natural gas Northern Ireland.

All performance and demand data were recorded at 30 minute intervals and compiled into daily, weekly, monthly and yearly parameters and used to determine the µ-CHP's performance. The variables recorded during the field trial provide a comprehensive description of the WhisperGen Stirling engine µ-CHP technology under realistic operating conditions.

3.1 µ-CHP Energy Performance

During operation, for a given quantity of gas used, the µ-CHP unit generates both heat and electrical energy while incurring some energy losses. This is expressed mathematically as:

$$Q_f = Q_h + E_{el} + E_{loss} \quad (1)$$

3.1.1 μ-CHP System Efficiency

There are three different system efficiencies that are important in measuring the performance of μ-CHP systems: the system thermal efficiency, the system electrical efficiency and the system overall efficiency which explain how much and why the energy (in the form of combustible fuel) being supplied to the system is lost [23].

The μ-CHP unit's thermal efficiency is the ratio of total thermal energy output (in the form of heat) produced to the total fuel (higher calorific value, HCV) energy supplied to the system. This relationship is described in Eq. 2 as [23]:

$$\eta_{th,\mu\text{-}chp} = \frac{Q_h}{Q_f} \quad (2)$$

The μ-CHP unit's electrical efficiency is the ratio of total electrical energy output produced to the total fuel energy (HCV) supplied to the system. This relationship is described in Eq. 3 as [23]:

$$\eta_{el} = \frac{E_{el}}{Q_f} \quad (3)$$

The μ-CHP unit's overall efficiency is the ratio of total electrical and thermal energy produced to the total fuel energy (HCV) supplied to the system. This value is found by adding the electrical efficiency and the thermal efficiency and is described in Eq. 4 as [23]:

$$\eta_{overall} = \frac{E_{el} + Q_h}{Q_f} = \eta_{el} + \eta_{th,\mu\text{-}chp} \quad (4)$$

3.3 Economic Analysis

The economic analysis involved comparing the performance of the WhisperGen μ-CHP unit against that of a condensing gas boiler retrofitted in a domestic dwelling. It was assumed that a consumer would choose a gas boiler or a μ-CHP given the former is the lowest cost technology for conveniently producing heat where a natural gas supply exists. The performance characteristics were evaluated to undertake a cost-benefit analysis of each heating system.

In analysing the economic performance of the μ-CHP unit in the dwelling, it was considered that the grid would meet the top-up electrical energy demand or supply the whole electrical demand if the μ-CHP were not running; while for the condensing gas boiler solution, all electricity used in the dwelling is imported from the grid.

Two key parameters used to determine the economic benefits of the μ-CHP unit were gas and electricity tariffs [11]. In the Republic of Ireland, the largest energy retailers providing gas and electricity are Bord Gáis and Electricity Supply Board (ESB) Electric Ireland respectively. For this evaluation and to simplify the costing the standard gas and electricity tariff for 2011 in Ireland were used. Table 3 shows the parameters used in the economic analysis. The export tariff paid by electricity retailers for electricity from the first 3,000 kWh of microgeneration units in the Republic of Ireland is 19 c/kWh [9]. Table 4 shows the heating system parameters. For fully pumped hot water based gas-fired central heating systems, the boiler seasonal efficiency is required to be greater than 86% [24, 25].

The economic analysis considered the following parameters: installation capital cost, annual fuel costs, annual maintenance cost, imported electricity cost, exported electricity revenue generated to provide an overall net cost saving compared to a condensing gas boiler. The unit was considered to have a negligible salvage value and disposal cost, particularly when discounted over its lifespan, so this was ignored. These parameters are calculated using Eqs. 5-11 and the parameters listed in Table 3.

3.3.1 Incremental Payback

The incremental payback is the time period to recover the extra investment of purchasing the μ-CHP unit over the condensing gas boiler. It is calculated using Eq. 5 given as [29]:

$$IPB = \frac{C_{\mu\text{-chp}} - C_{boiler}}{\Delta AS} \quad (5)$$

3.3.2 *μ-CHP Unit Operating Cost*

The total operating cost of the μ-CHP unit is calculated as the sum of the fuel cost, maintenance cost and the cost of importing electricity, less the cost of displaced electricity imported from the grid and the revenue accrued from electricity exported to the grid. This is represented mathematically as:

$$C_{\mu\text{-chp}} = C_{\mu\text{-chp,f}} + C_{\mu\text{-chp,m}} + E_{imp}T_{imp} - E_{exp}T_{exp} \quad (6)$$

The μ-CHP maintenance cost is calculated using Eq. 7 given as:

$$C_{\mu\text{-chp,m}} = Q_h T_{\mu\text{-chp,m}} \quad (7)$$

The cost of fuel consumed by the μ-CHP unit is calculated using Eq. 8 given as:

$$C_{\mu\text{-chp,f}} = \frac{100 \cdot Q_h T_g}{\eta_{th,\mu\text{-chp}}} \quad (8)$$

3.3.3 *Condensing Boiler Operating Cost*

The total operating cost of the boiler is calculated as the sum of the fuel cost, maintenance cost and the cost of importing electricity from the grid. It is represented mathematically as:

$$C_{boiler} = C_{bf} + C_{mb} + E_{imp}T_{imp} \quad (9)$$

The cost of fuel consumed by the condensing gas boiler is calculated using Eq. 10 given as:

$$C_{bf} = \frac{100 \cdot Q_{hb} T_g}{\eta_b} \quad (10)$$

The boiler maintenance cost is calculated using Eq. 11 given as:

$$C_{mb} = Q_{hb} T_{bm} \quad (11)$$

3.4 GHG Emission Analysis

The GHG emission analysis estimates the quantity of CO_2 emissions avoided by the μ-CHP unit compared to the condensing gas boiler, assuming a greater overall efficiency for the former (which generates both heat and electricity) compared to the latter (which generates heat only). The electricity generated by the μ-CHP unit is considered to displace grid supplied electricity thereby resulting in a reduction in generation from centralised power plants. Therefore, both the 1,383 kWh of electricity consumed on-site and the 680 kWh of electricity exported were considered to reduce CO_2 emissions from the house fitted with the μ-CHP unit.

The GHG emission analysis therefore consists of evaluating the performance of the μ-CHP unit using CO_2 emissions savings relative to the condensing gas boiler fitted in the house. This requires us to evaluate the emissions associated to a house fitted with a condensing gas boiler. These emissions are due to heat generated by the gas boiler and electricity imported from the grid. On the other hand, emissions associated to a house fitted with a μ-CHP unit are due to imported grid electricity and the heat generated by the unit less emissions due to electricity generated. The base year (2011) CO_2 intensities of grid supplied electricity and natural gas in Ireland were 0.504 $kgCO_2/kWh$ [28] and 0.18 $kgCO_2/kWh$ [30] respectively.

3.4.1 μ-CHP

In a house fitted with a μ-CHP unit, the total quantity of emitted CO_2 is the sum of the CO_2 associated with electricity imported from the grid and the quantity of CO_2 associated with heat generated minus the quantity of avoided CO_2 emissions associated with electricity generated by the μ-CHP unit that is used on-site and/or exported to the grid. This is expressed as:

$$EC_{\mu-chp} = E_{imp}CI_{ge} + \frac{100 \cdot Q_h CI_{ng}}{\eta_{th,\mu-chp}} - (E_{on} + E_{Exp})CI_{ge} \tag{12}$$

3.4.2 Condensing Gas Boiler

In a house fitted with a condensing gas boiler, the amount of CO_2 emitted is the sum of emissions due to electricity imported from the grid and heat generated by the boiler. This is expressed as:

$$EC_b = E_d CI_{ge} + \frac{100 \cdot Q_{hb} CI_{ng}}{\eta_{th,b}} \tag{13}$$

4 Results and Discussion

4.1 Energy Analysis

Fig. 2 shows an energy balance diagram for the μ-CHP unit which summarises the results of the data obtained from the field trial. It can be seen from the figure that for a given quantity of gas used by the μ-CHP unit, on average 76.5% is converted into heat, 7.9% into electricity while losses account for 15.6%.

4.1.1 Heat and Electricity Demand

The energy demand of the dwelling can be divided into heat and electricity. The dwelling had an annual heat and electrical energy demand of 20,095 kWh and 6,663 kWh respectively. Fig. 3 shows the monthly total electrical and heat energy use of the dwelling during the field trial period. The maximum monthly heat and electrical energy consumption were 3,138 kWh in January 2005 and 667 kWh in December 2004 while the corresponding minimum values were 531 kWh in August 2004 and 470 kWh in June 2005. The electrical energy use did not vary much throughout the year while the heat energy demand was highest during the winter months (hot water and space heating) and relatively constant during the summer months (hot water only). The electrical energy consumption varied seasonally but the average electrical energy demand during the summer months was 500 kWh, while for the winter months it was 606 kWh. Heat use also varied seasonally with average values of 761 kWh during the summer months and 2,870 kWh during the winter months.

4.1.2 Heat and Electricity Generated

The µ-CHP unit operated reliably achieving an availability of 97%. The 3% downtime was as a result of technical difficulties and teething problems associated with the infancy of the µ-CHP unit. Monthly demand profiles were used to determine the amounts of heat and electricity required by the dwelling. Fig. 4 shows variations in the monthly heat and electrical energy generated by µ-CHP unit during the field trial period. During the field trial period, the µ-CHP generated 2,063 kWh_e and 20,095 kWh_{th} of electricity and heat respectively. The maximum heat and electrical energy generated were 3,138 kWh and 337 kWh respectively in January 2005. The minimum heat generated was 531 kWh in August 2004 while the minimum electricity generated was 49 kWh in August 2004 and June 2005.

4.1.3 Electrical Energy Balance

Electricity output from a heat-led µ-CHP unit is determined by the household's heat demand that varies considerably depending on the building type, building standard, location of the house and occupant behaviour [31]. Fig. 5 shows monthly plots of electricity generated, exported and total electricity used on-site during the field trial period. The electrical energy generated and used on-site varied seasonally but the average monthly figure during the summer months was 52 kWh, while it was 296 kWh during the winter months. The µ-CHP unit provided 20.8% of the dwelling's electrical requirement on an annual basis.

Of the 2,063 kWh of electricity generated by the µ-CHP unit during the year, 1,383 kWh was used on-site while 680 kWh was exported to the grid. 5,280 kWh therefore had to be imported to meet the electricity demand of the dwelling.

As expected, the greatest amount of electricity exported was for the period October 04 to April 05. This was partially due to the unit being signalled to start up early morning to meet the required room temperature when the household's electricity demand was low. The maximum electricity exported was 101 kWh in January 05 while the minimum electricity exported was 18 kWh in August 04. The maximum amount of electricity imported was 519 kWh in October 04 while the minimum amount electricity imported was 321 kWh in February 05.

4.1.4 System Efficiencies

Calculations of energy efficiency were carried using metered fuel input, electrical output and heat output. Fig. 6 shows the µ-CHP unit's efficiencies during selected days for each month of the monitoring period. The electrical efficiency varied from 6.1% to 9.1% but the average annual efficiency was 7.9%. The low electrical efficiency of the µ-CHP unit reflects its high heat to power ratio (HPR) which varied from 9.1 to 12.7 over the period. A maximum value of overall efficiency of 92.2% was recorded with an average value of 86.3% calculated for the whole year.

4.2 Economic Analysis

A detailed financial appraisal was carried out to assess the economic viability of the µ-CHP unit, given that its capital and initial installation costs are considerably higher than those for a condensing gas boiler. The financial performances of the condensing gas boiler and the µ-CHP unit were evaluated over their life cycle. The economics of the µ-CHP unit is dominated by natural gas fuel (the main running cost) as well as imported and displaced electricity costs. Periodic maintenance represents another operating cost. The maintenance requirements for µ-CHP units are always higher compared to conventional gas boilers. However, some µ-CHP units (e.g. Stirling engines units) are approaching the low maintenance requirements of conventional gas boilers.

The economics of the heating system with the µ-CHP unit is highly dependent on the magnitude of residential energy consumption, especially the thermal energy demand [11, 32] since this dictates the µ-CHP assets' utilisation rate and payback periods. As was expected the annual fuel costs of the condensing gas boiler was lower than that of the µ-CHP unit due to its higher thermal efficiency which leads to lower fuel consumption. The dwelling fitted with a condensing gas boiler however has a higher cost of imported electricity than that for the µ-

CHP unit since the boiler does not produce any electricity. The values of exported and displaced electricity are therefore important factors in the economic performance of the µ-CHP unit. The µ-CHP unit was found to have a lower net annual operating cost compared to the condensing gas boiler.

4.2.1 Monthly Operational Cost Savings

The monthly cost savings (€/month) for the existing dwelling are based on the gas and electricity prices in the Republic of Ireland given in Table 5. Fig. 7 shows the monthly operational cost savings achieved by the µ-CHP unit during the field trial. Moran et al. [23] reported that at certain fuel and electricity prices, µ-CHP systems can produce noticeable savings in monthly energy costs. The factors which made these savings possible were the cost of gas, their high generating efficiency and the high availability of the unit. The distribution of savings is shown in Fig. 7 which shows that the highest monthly saving was in January 2005 at €37.60 and lowest in August 2004 at €0.50. The average monthly operating saving was €15.00.

4.2.2 Annual Operational Cost Savings

The annual cost savings achieved by the µ-CHP unit was €180. The incremental cost of the µ-CHP unit was €2,500 more than a condensing gas boiler. This therefore requires a simple, undiscounted payback period of 13.8 years to recover the additional investment.

Table 5 shows a summary of the results of the comparative economic appraisal of the µ-CHP unit against the condensing gas boiler. The electricity consumed by the condensing gas boiler and µ-CHP unit circulation pumps was considered to be negligible and is therefore not included in the analysis. For the µ-CHP unit the sum of maintenance, fuel and electricity costs add up to a total operating cost of €1,883. If we include the revenue of €129 from exported electricity, this would result in a total operating cost of 1,754.

Over a 15 year operating period and a discount rate of 10% [33], assuming no escalation in maintenance cost, electricity and gas prices, the net present value (NPV) for the condensing gas boiler and µ-CHP units were -€16,310 and -€15,965 respectively. The higher

NPV of the μ-CHP unit shows that it is economically better to invest in the μ-CHP unit rather than the condensing gas boiler. The Carbon Trust field trial [10] showed an economic benefit of £158 annually (€180 in the Republic of Ireland) and simple incremental payback period of 16 years (13.8 years in Ireland) over the condensing gas boiler.

4.3 GHG Emission Analysis

CO_2 emissions reduction is the primary environmental advantage of the μ-CHP. The measured carbon savings of the μ-CHP are benchmarked against a condensing gas boiler and grid supplied electricity. Table 6 shows CO_2 emissions for a house fitted with a conventional gas boiler and a μ-CHP unit. The total CO_2 emissions for the μ-CHP unit and condensing gas boiler were calculated using Eqs. 12 and 13 respectively. The quantity of CO_2 emissions of heat generated were calculated using the amount of gas consumed by the μ-CHP unit and condensing gas boiler taking into account their thermal efficiencies.

The data shown in Table 6 are in line with the manufacturer's predictions of the environmental advantage of avoided CO_2 emissions associated with the μ-CHP. Overall, the dwelling fitted with a μ-CHP system and topping up its electricity needs from the grid generated 2,063 kWh of electricity. This resulted in emissions savings of 1,040 kgCO_2 per annum (16.1%) less than one fitted with a condensing gas boiler and importing all its electricity needs. Taking the results in Table 6 over the estimated lifespan of 15 years, assuming no changes in efficiency and no further reduction in CO_2 intensity of grid supplied electricity the μ-CHP unit would save 15.6 tCO_2. The findings of this study are an improvement of those of the field trial runs by the Carbon Trust [10] which found that at the current stage of μ-CHP technology development, limited contributions to CO_2 reduction can be achieved. The limited CO_2 emission savings by the Carbon Trust study is as a result of their assumption that the electricity generated by the μ-CHP unit was carbon neutral. They therefore recommended that considerable improvements in the technology would be required and that the use of the μ-CHP unit would make sense in countries/regions with high emissions intensity of electricity production. Our findings therefore reveal that the WhisperGen Mk IV Stirling engine μ-CHP unit has the capacity to generate electricity in the home and contribute positively to the concept of distributed power generation while reducing CO_2 emissions.

It is interesting to note that both Ireland and the UK are currently engaged in the construction of considerable quantities of renewable energy (mainly wind) which will result in the further decarbonisation of the electricity system. If for example, the emissions intensity of electricity were to fall to 0.4 $kgCO_2$ then emissions savings from the μ-CHP with grid top-up will decrease to 855 $kgCO_2$ per annum or 12.4% over the boiler with grid import electricity.

5. Conclusions

The core question investigated in this paper is the extent to which μ-CHP can reduce life cycle costs, emissions and energy requirements in a domestic dwelling in Ireland and the extent of its attractiveness to domestic homeowners, energy suppliers and policy makers.

Operating a WhisperGen Mk IV Stirling engine μ-CHP unit in the house studied resulted in primary energy savings compared to a standard condensing gas boiler. It resulted in an energy saving of 2,063 kWh of electricity and generated a thermal output of 20,095 kWh during the field trial period, operated for 2,512 hrs and generated an annual cost saving of €180. This resulted in an incremental simple payback period of 13.8 year over the condensing gas boiler. The μ-CHP unit used 2,889 kWh of gas more than the condensing gas boiler. It reduced the quantity of imported electricity by 20.8%. A major achievement was the reliability of the μ-CHP unit, which achieved an availability of 97% for the year.

The monthly overall efficiency fluctuated from 78.6% in August 2004 to a maximum value of 92.3% in December 2004 with a yearly average operating overall efficiency of 86.3%. The heat outputs measured during the field trial were similar to those quoted by the manufacturer generating a maximum heat output of 8.4 kW.

While the economic performance appears attractive, the disadvantage of the WhisperGen Mk IV Stirling engine μ-CHP unit is its high capital cost, a deterrent to purchasers. In order to achieve a reasonably low incremental payback period of say 5 years, the additional cost of the µ-CHP unit over the condensing gas boiler should be no more than €900.

CO_2 emissions reduction was the primary environmental advantage of the µ-CHP specified by the manufacturer and cited in literature. The analysis in this study showed that there was a decrease of 1,040 $kgCO_2$ per annum from the fossil fuel driven µ-CHP unit compared to a condensing gas boiler fitted in the house. Given its sensitivity to the CO_2 emissions intensity of grid electricity and the on-going decarbonisation of the electrical generation systems both in Ireland and the UK, very significant performance improvements will be needed for this technology to compete as an environmentally-friendly alternative to conventional energy technologies.

The Whispergen Mk IV µ-CHP unit was a prototype, based on Stirling engine technology. The concept was to generate 8 kW of heat and 1 kW of electricity for application in the domestic sector. The purpose of the field trial from June 2004 to July 2005 was to evaluate the economic, energy and emission performance of the prototype Whispergen Mk IV µ-CHP unit installed in a dwelling with a hydronic heating system and assess the feasibility of this prototype technology as a competitive alternative to a condensing gas boiler fitted in a house. The Whispergen Mk IV µ-CHP unit's main advantage compared to a conventional condensing gas boiler is that it produces 1 kW of electrical power. This information is very valuable for researchers, policy makers, academics and the wider scientific community. The Whispergen Mk IV µ-CHP unit is no longer state-of-the-art and is superseded by the Whispergen Mk V unit, incorporating a supplementary burner. It was introduced in 2006 to provide additional flexibility, making the unit suitable for larger dwellings. The Whispergen Mk IV µ-CHP unit is a compact product, very reliable and was in development for 15 years.

The Whispergen Mk V µ-CHP unit delivers a thermal output of 7 kW_{th} (engine) plus 5kW_{th} (burner) installed into the hydronic heating system fitted with a 300 litre storage tank nowadays. Because of the greater thermal output and larger storage capacity, this unit is achieving even higher annual savings and greater reduction in CO_2 emissions.

Acknowledgements

The authors would like to thank Gwyneth Scott of Northern Ireland Electricity for the data used in the analyses in this paper and Phoenix Gas, Northern Ireland.

Nomenclature

C_{boiler}	total operating cost of boiler (€)
C_{bf}	boiler fuel cost (€)
$C_{\mu\text{-chp}}$	total operating cost of µ-CHP unit (€)
$C_{\mu\text{-chp,f}}$	µ-CHP fuel cost (€)
$C_{\mu\text{-chp,m}}$	µ-CHP maintenance cost (€)
C_{mb}	total boiler maintenance cost (€)
CI_{ge}	the carbon intensity of grid electricity ($kgCO_2$/kWh/Pa)
CI_{ng}	carbon intensity of natural gas ($kgCO_2$/kWh)
CI_b	carbon intensity of conventional boiler ($kgCO_2$)
E_d	the total electricity demand (kWh)
E_{el}	electrical energy generated (kWh)
E_{exp}	electricity generated by µ-CHP exported to grid (kWh)
E_{imp}	electricity imported from the grid (kWh)
E_{loss}	energy losses (kWh)
E_{on}	electricity generated by µ-CHP used on-site (kWh)
EC_b	emitted carbon associated with electricity imported from the grid ($kgCO_2$/Pa)
$EC_{\mu\text{-CHP}}$	emitted carbon associated with electricity imported from the grid ($kgCO_2$/Pa)
IPB	incremental payback period (years)
kW_e	kilowatt hour of electricity
kW_{th}	kilowatt hour of heat
Q_h	quantity of heat generated by µ-CHP (kWh)
Q_{hb}	quantity of heat generated by the boiler (kWh)
Q_f	quantity of fuel used (kWh)
T_{imp}	tariff of imported electricity (€/kWh)
T_{exp}	tariff of exported electricity (€/kWh)
T_{bm}	tariff of unit boiler maintenance (€/kWh)
T_g	gas tariff (€/kWh)
$T_{\mu\text{-chp,m}}$	tariff of µ-CHP maintenance (€/kWh_{th})
ΔAS	incremental annual saving (€/year)
η_{el}	electrical efficiency (%)
$\eta_{overall}$	overall efficiency of the µ-CHP unit (%)
$\eta_{th,b}$	thermal efficiency of condensing gas boiler (%)
$\eta_{th,\mu\text{-chp}}$	thermal efficiency of µ-CHP unit(%)

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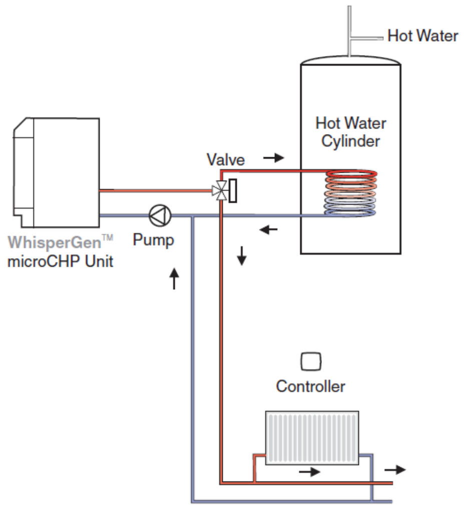

Fig 1. Installation diagram of the WhisperGen Stirling engine μ-CHP unit used in the residential dwelling [18]

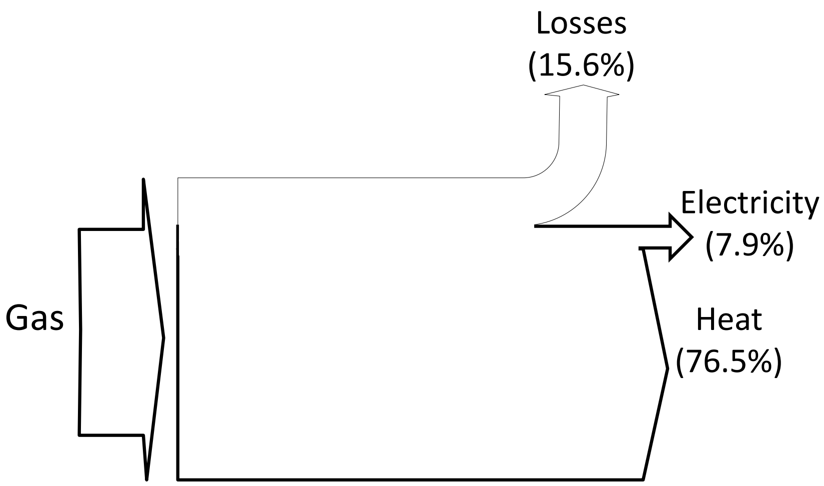

Fig. 2. Energy balance diagram for the μ-CHP unit

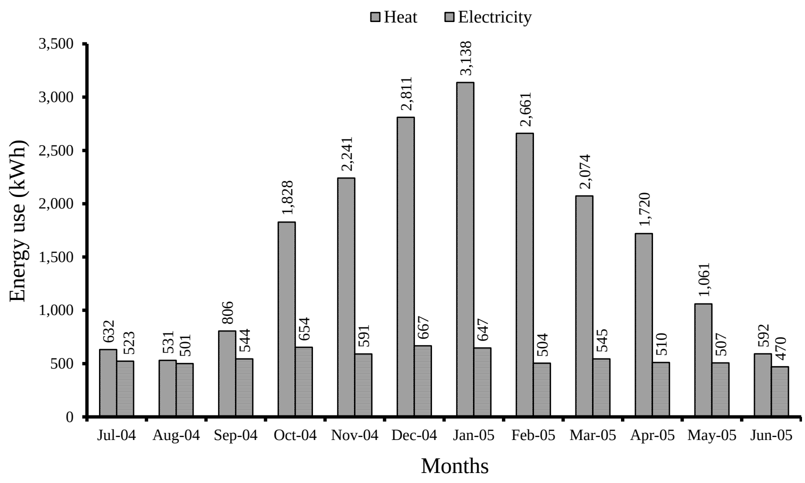

Fig. 3. Heat & electrical energy demand profile for the field trial dwelling over a Year

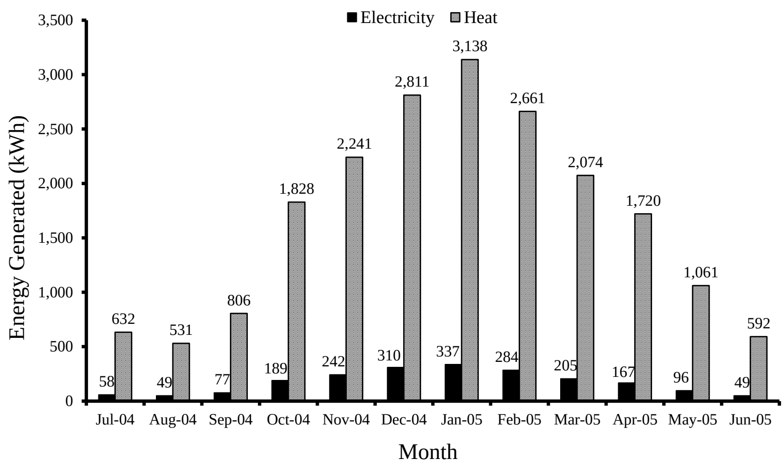

Fig. 4: Total monthly heat and electricity generated by the µ-CHP unit

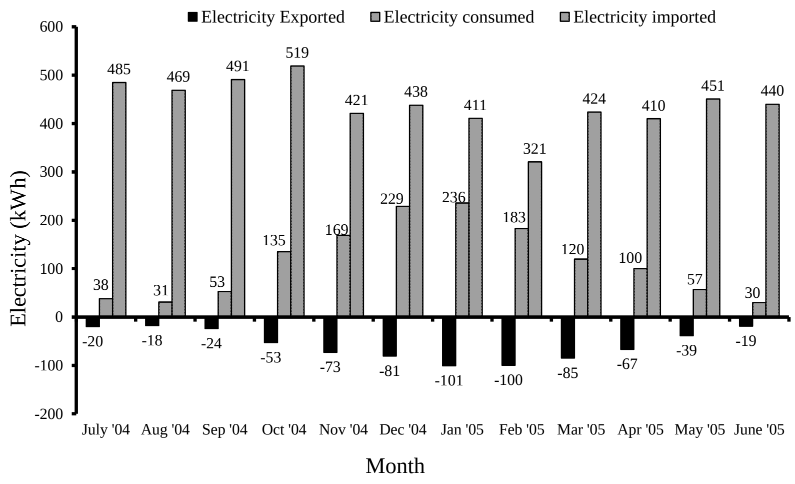

Fig. 5. Electricity imported, exported and total electricity used on site during the field trial period

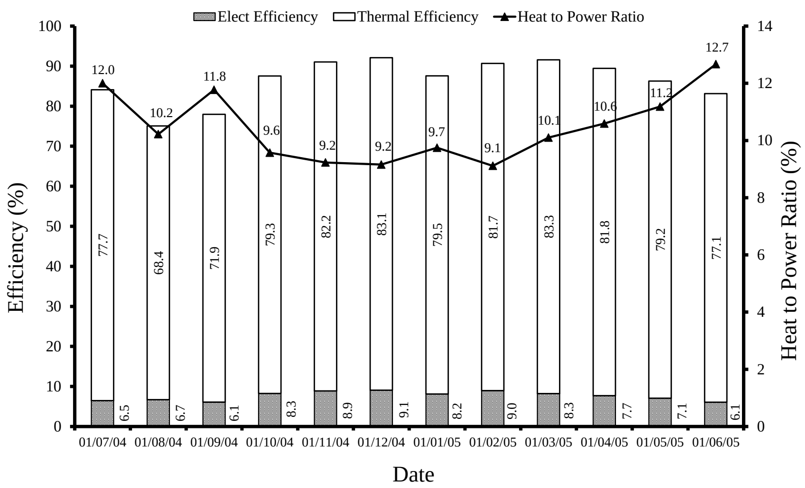

Fig. 6. Efficiencies and HPR for selected days for each month

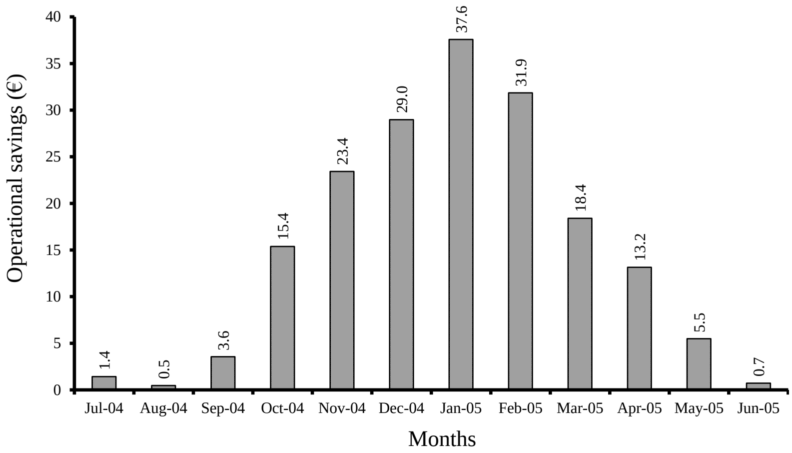

Fig. 7. Monthly cost savings achieved by the μ-CHP unit

Tables

Table 1: Technical specifications of the μ-CHP unit [21]

Parameters	Unit	Values
Model		Mk IV AC gas fired
Engine cycle		4 cylinder double acting Stirling
Main burner		Premix surface burner
Maximum heat output	kW	8
Nominal mode	kW	up to 7
Duty cycle		1 – 24 hour cycle
Max installation weight	kg	137
Dimensions (HxWxD)	mm	840 x 490 x 560
Fuel		Natural gas
Gas supply pipe size	mm	22
Fuel consumption	m^3/h	Maximum burner firing rate 1.55
Seasonal efficiency	%	80-90
Electrical supply	V/Hz	230/50 (Nominal grid voltage)
Electrical Output		Up to 1000 Watts AC at 220-240V
Grid connection		4 pole induction generator
Enclosure		Floor mounted, free standing
Connections		Standard pluming connections

Table 2: Technical specifications of the condensing gas boiler [22]

Controls	Unit	Value
On/Off switch with reset		Yes
User adjustable CH temperature		Yes
Heat input	kW	15
Maximum heat output (80/60°C)	kW	14.81
Maximum heat output (50/30°C)	kW	15.9
Main burner		Premix burner
Max installation weight	kg	38
Dimensions (HxWxD)	mm	276 x 376 x 262
Fuel		Natural gas
Gas supply pipe size	mm	22
SEDBUK (2005) Rating (Band)		A
Fuel consumption	m^3/h	1.6
Seasonal efficiency	%	90.4
Electrical supply	V/Hz	230/50
Power Consumption	W	50
Mounting plates		Brackets
CH flow and return pipe size	mm	22

Table 3: Parameters used in economic analysis

Parameter	**Unit**	**Value**
Grid Electricity Cost $_{(2011)}$	c/kWh	14*
Electricity Export price $_{(2011)}$	c/kWh	19+
Discount Rate	%	10
System Life	Years	15[1]

*Electricity Supply Board Electric Ireland [26]

+Sustainable Energy Authority of Ireland [27]

[1]From manufacturer's data

Table 4: Heating system Parameters

Parameter	**Unit**	**Value**
Boiler efficiency (HCV)	%	86.0*
Gross efficiency of μ-CHP	%	84.4+
μ-CHP Electrical efficiency	%	7.9+
μ-CHP thermal efficiency	%	76.5+
Maintenance cost of μ-CHP	c/kWh	0.9[2]
Maintenance cost of condensing gas boiler	c/kWh	0.4[2]
Gas cost	c/kWh	3.9[1]
Condensing gas boiler capital cost	€	1,200[4]
μ-CHP capital cost	€	3,500[4]
Boiler installation cost	€	400[3]
μ-CHP installation cost	€	600[3]
Condensing gas boiler annual maintenance cost	€	90[5]
μ-CHP annual maintenance cost	€	120[6]

*Recommended seasonal baseline efficiency [24, 25]
+Measured from the field trial
[1]Gas tariff [28]
[2]Calculated values from Eqs. 7 and 11
[3]Obtained from suppliers
[4]Obtained from manufacturers
[5]Bord Gáis Energy
[6]Obtained from supplier

Table 5: Summary of result

Description	Condensing gas boiler	µ-CHP
Revenue		
Exported electricity (€)	0	129
Costs		
Annual maintenance (€)	90	120
Annual fuel (€)	911	1,024
Imported electricity (€)	933	739
Annual total operating (€)	1,934	1,754
Annual saving (€)	0	180
Incremental capital (€)*	0	2,500
Economic appraisal		
Incremental payback period (years)	0	13.8
Net present value (€)	-16,310	-15,965

*This is the difference between the capital cost of the µ-CHP unit and the condensing gas boiler.

Table 6: CO_2 emissions for a house with a conventional boiler and µ-CHP unit

Parameters	Condensing gas boiler ($kgCO_2/pa$)	µ-CHP ($kgCO_2/pa$)
CO_2 emissions of imported electricity	3,358	2,661
CO_2 emissions of heat generated	4,205	4,728
Avoided emissions due to reduction of electricity production in power plant	-	-1,040
Total CO_2 emissions	7,563	6,349
Avoided emissions due to µ-CHP		-1,214
Percentage of avoided emissions (%)		16.1

Reviewer Comments:

Reviewer #2: The revision of the paper helped a lot to provide a better understanding for the reader and to eliminate deficiencies. However, a few shortcomings are remaining and they should be revised as follows before publishing:

page 8, Table 1: The dimensions for the WhisperGen unit are obviously wrong. The unit shows the size of i.e. a dish washer like 490 x 840 x 560 mm (WxHxD)

The dimensions for the WhisperGen unit are incorrect. The dimensions have been corrected in table 1to the values stated 490 x 840 x 560 mm (WxHxD)

On page 10, 2nd paragraph the information has been added that the flow of the natural gas for running the CHP unit was measured in cubic meters. However, there needs to be a additional comment how this number has been converted into the corresponding energy Qf. What number for higher caloric value of the gas has been used and where does it come from? How was the gas flow measured in cubic meters converted to the flow in Standard m^3?

The following explanation has been added to the second paragraph of page 10:

A conversion factor of 11.4 was used to convert cubic meters into the corresponding energy (Q_f) in kWh. The WhisperGen manufacturer uses gross or higher calorific value (GCV), when stating the efficiency of their μ-CHP. All gas was purchased on the basis of its higher calorific value. The number for higher caloric value of the gas was 38.0 MJ/m^3 and this value was obtained from the gas retailer Phoenix natural gas Northern Ireland.

page 14, eq. 6: The author did not agree to the comment of the reviewer saying that the term -E_on*T_imp is wrong in equation 6 and should be omitted. However, the calculation resulting in the data displayed in table 5 was derived just without taking this term into consideration; hence, just in a way the reviewer requested. So, why does the author not delete the term in equation 6?

C_CHP = C_CHP,f + C_CHP,m + EimpTimp - EonTimp - EexpTexp

using the numbers from table 5:

1,754 = 1,024 + 120 + 739 (- EonTimp not needed) – 129

The term (- $E_{on}T_{imp}$) has been deleted from equation 6 as suggested by the reviewer.

page 15, section 3.4: Treating the electricity generated by the CHP unit as CO2 free or neutral is still a very course assumption. On the one hand, the author neglects the impact of the electricity exported to the grid on the electricity generation by power plants. On the other hand, the effect of the reduced import of electricity is included in the analysis and the results displayed in Table 6. This reduction of imported electricity is as well of minor impact on the electricity generation by power plants. Hence, the paper is in this respect not consistent, and the reviewer cannot understand, why the author refuses to take the reduction of electricity production in the power plants and the corresponding reduction of CO2-emissions into account, as well. It will not cause any major efforts, just one more line in Table 6, and the percentage of avoided CO2-emissions will become a little better for the CHP unit.

The assumption that the electricity generated by the CHP unit is carbon neutral has been removed. The quantity of CO_2 emissions avoided due to a reduction in the electricity generation in the power plant has been calculated and the results included in Table 6. Equation 12 has been modified to reflect the reduction in CO_2 emissions due to electricity generated by the µ-CHP unit.

page 15, eq. 12: In response to the 1st review it was stated that the term -E_on*CIge has been deleted from eq. 12, as suggested. However, the term is still part of the equation and should be removed.

Equation 12 has been modified to reflect the reduction in CO_2 emissions due to electricity generated by the µ-CHP unit.

page 20: the table should be labeled as Table 5 (not Table 3)

This table number has been changed and now reads Table 5

Finally, there should be at least a comment about the fact that the results were obtained from a CHP unit and a hydraulic system, which are no longer state of the art. This is not to discredit the results and the conclusions from the paper; evidently, they are still very valuable for the scientific community. But there should be a comment in a way that state of the art Micro-CHP units equipped with a proper storage tank nowadays gain even higher annual savings and even higher reductions in CO2-emissions.

The following have been added to the conclusions

The Whispergen Mk IV μ-CHP unit was a prototype, based on Stirling engine technology. The concept was to generate 8 kW of heat and 1 kW of electricity for application in the domestic sector. The purpose of the field trial from June 2004 to July 2005 was to evaluate the economic, energy and emission performance of the prototype Whispergen Mk IV μ-CHP unit installed in a dwelling with a hydronic heating system and assess the feasibility of this prototype technology as a competitive alternative to a condensing gas boiler fitted in a house. The Whispergen Mk IV μ-CHP unit's main advantage compared to a conventional condensing gas boiler is that it produces 1 kW of electrical power. This information is very valuable for researchers, policy makers, academics and the wider scientific community. The Whispergen Mk IV μ-CHP unit is no longer state-of-the-art and is superseded by the Whispergen Mk V unit, incorporating a supplementary burner. It was introduced in 2006 to provide additional flexibility, making the unit suitable for larger dwellings. The Whispergen Mk IV μ-CHP unit is a compact product, very reliable and was in development for 15 years.

The Whispergen Mk V μ-CHP unit delivers a thermal output of 7 kW_{th} (engine) plus 5kW_{th} (burner) installed into the hydronic heating system fitted with a 300 litre storage tank nowadays. Because of the greater thermal output and larger storage capacity, this unit is achieving even higher annual savings and greater reduction in CO_2 emissions.