Life Cycle Energy and Carbon Analysis of Domestic Combined Heat and Power Generators

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***Abstract*—Micro Combined Heat and Power (micro-CHP) generators combine the benefits of the high-efficiency cogeneration technology and microgeneration and is being promoted as a means of lowering greenhouse gas emissions by decentralizing the power network. Life Cycle Assessment of energy systems is becoming a part of decision making in the energy industry, helping manufacturers promote their low carbon devices, and consumers choose the most environmentally friendly options.**

This report summarizes a preliminary life-cycle energy and carbon analysis of a wall-hung gas-powered domestic micro-CHP device that is commercially available across Europe. Combining a very efficient condensing boiler with a Stirling engine, the device can deliver enough heat to cover the needs of a typical household (up to 24kW) while generating power (up to 1kW) that can be used locally or sold to the grid. Assuming an annual heat production of 20 MWh, the study has calculated the total embodied energy and carbon emissions over a 15 years operational lifetime at 1606 GJ and 90 tonnes of CO_2 respectively.

Assuming that such a micro CHP device replaces the most efficient gas-powered condensing boiler for domestic heat production, and the power generated substitutes electricity from the grid, the potential energy and carbon savings are around 5000 MJ/year and 530 kg CO_2/year respectively. This implies a payback period of the embodied energy and carbon at 1.32 - 2.32 and 0.75 - 1.35 years respectively.

Apart from the embodied energy and carbon and the respective savings, additional key outcomes of the study are the evaluation of the energy intensive phases of the device's life cycle and the exploration of potential improvements.

***Index Terms*—Embodied Energy-Carbon, Life Cycle Assessment, Micro-CHP, Distributed Microgeneration, Stirling Engine, Energy Efficiency, Domestic Boiler.**

I. INTRODUCTION

ENERGY systems in most European countries are experiencing a transformation in recent years, following the generalized trend of a sustainable development strategy. Sustainability in the power sector can be achieved by reducing the carbon content of the current energy mix and by reducing the energy demand itself by means of efficient generation and consumption.

An additional trend among people is the increasing awareness of their environmental footprint, by means of energy use and carbon emissions. This awareness has led to the development of standardized methods that evaluate the environmental behavior of products and services and address their possible environmental impacts assessing not only their operational life, but also the manufacturing and the end-of-life procedures.

This work presents a detailed if preliminary life-cycle energy and carbon analysis of a domestic micro-CHP generator that is commercially available in several countries across Europe. The analysis calculates the energy consumption and carbon emissions related to all stages of the life-cycle of the generator, and compares them to those of a state-of-the-art conventional thermal device (A-rated condensing boiler) and power from the grid. The result is an estimate of the potential energy and carbon savings deriving from replacing a conventional unit by a micro-CHP.

A. *Micro Combined Heat and Power Generation*

Micro cogenerators combine two distinct elements: the simultaneous generation of heat and power (CHP) and the distributed small-scale electricity production. Large-scale CHP systems have been used since the beginning of the 20th century while decentralized microgeneration is rather a modern trend.

1) Cogeneration: Combined heat and power generation is a mature technology that makes efficient use of the primary energy contained in fuels to generate a useful dual product of power and heat. The principle of cogeneration is to supply 'both electricity and usable thermal energy (heat and/or cooling) at high efficiency and near the point of use' [1]. The heat lost in modern power plants is typically around one-third to a half of the primary energy of the fuel. However, in CHP systems it is used for industrial processes or space heating [2].

Apart from drastically increasing the efficiency of electricity generation, CHP systems benefit from lower distribution losses, since they are usually located close to the point of consumption. Economic benefits are also very important for medium and small users of the CHP technology, as the increased initial cost of the device is amortized by the fuel savings and the gains from selling excess power to the grid at high retail prices. Additionally, all the above contribute to better environmental behavior when compared to conventional power generators.

2) Microgeneration: Distributed microgeneration is being promoted as a useful tool of lowering carbon emissions, by means of decentralizing the energy system, reducing power transmission losses and saving grid capacity. The environmental benefits of microgeneration relate to carbon mitigation due to reduced network losses and by offsetting carbon intensive grid electricity. Additionally, due to their peak-load profile (especially micro CHP), they can be used to support the system at high demand levels [3]. From an economic point of view, microgeneration devices offer an incremental and low risk investment. They offer energy and financial benefits, without the risks associated with large one-off energy generators.

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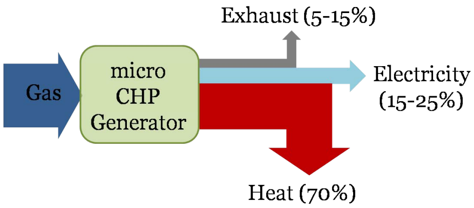

Fig. 1. Typical micro CHP energy flow

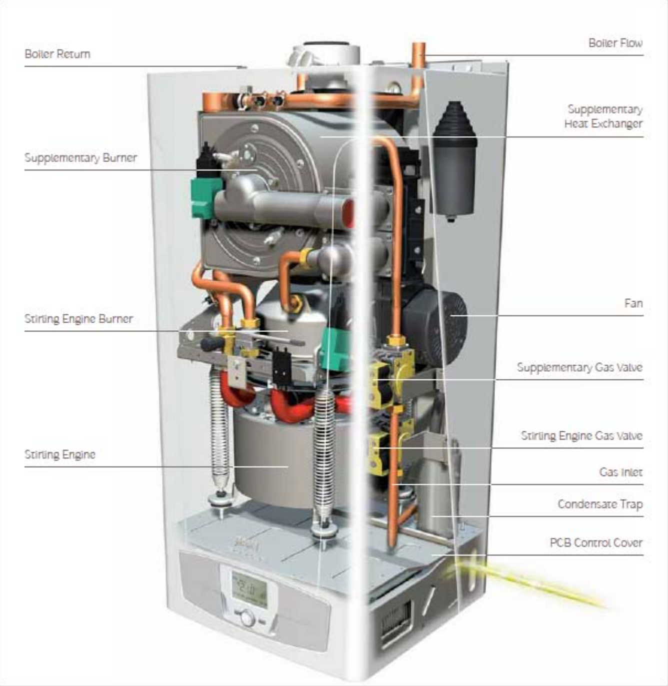

Fig. 2. General Layout of a Stirling Engine micro-CHP Device

On the other hand, microgenerators cannot be considered as just a scaled-down version of large-scale power plants. They are less efficient and the cost for every generated kWh is significantly higher. A decentralized generation regime would impose alteration of the existing grid infrastructure in order to guarantee network stability. Finally, due to the loss of economies of scale, their embodied energy and carbon per generated kWh is potentially higher, and therefore detailed life-cycle assessments should be carried out in order to evaluate their environmental behavior and their real energy and carbon savings.

B. *Micro-CHP system using a Stirling engine*

The domestic micro-CHP system that was investigated in this study is a dual energy system, similar in size and appearance to a modern wall-hung condensing boiler. It combines a free-piston Stirling engine that can generate 1 kW of power and 6 kW of heat with a high efficiency condensing boiler that produces the supplementary thermal power needed to cover all the needs for space heating and hot water of a household. It is virtually noise and vibration free, therefore it can be fitted in a range of locations, including the kitchen.

The thermal and electrical efficiencies of the device are 75.8% and 7.5%, leading to an overall efficiency of 83.3%, which is typically much higher than the overall efficiency of the combination of a SEDBUK Band A boiler (in excess of 90% efficient) and electricity from the grid. It benefits from the fact that the power generated is consumed on-site, eliminating any losses in the transmission and distribution network. Additionally, it is heat driven, that means that it tends to produce power at times of peak demand, maximizing the chance of consuming it locally, and increasing the energy savings [4].

1) Total Generation Forecast: Assuming an annual heat demand of 20 MWh which is the typical needs of a household in the UK, and a lifetime of 15 years, the expected total gas consumption of such a device is 397 MWh, while the total thermal and electric energy generation are expected to be 301 MWh and 30 MWh respectively.

II. RESEARCH METHOD FOR ENERGY AND CARBON AUDIT

Increased environmental awareness has created the need for development of objective techniques that evaluate the impact of products and services to the environment. Life Cycle Assessment (LCA) is a standardized process (ISO 14040), that considers the environmental aspects of a product or service throughout its life cycle and provides a comprehensive view of its environmental behavior [5].

The technique used in this work to estimate the overall energy consumption and carbon emissions associated with the entire life-cycle of the micro-CHP device is based on the LCA framework, however, it focuses on auditing these components rather than conducting a generic environmental impact analysis.

A. *Cradle to Grave Approach*

Although the measurement of the operational energy and carbon intensity of a product is rather straightforward, the estimation of the entire amounts involved in its life cycle is a much more complicated issue. It additionally takes into account the manufacturing and decommissioning phases of the product, giving an evaluation of its overall environmental behavior.

Embodied energy (carbon) of a material is the primary energy consumed (carbon released) throughout its lifetime. A cradle-to-grave approach includes all stages from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal, considering the transportation of materials, fuels and wastes throughout these phases [5].

B. *Life Cycle Assessment Framework*

Life Cycle Assessment is a holistic procedure that addresses all the material, energy and waste flows associated with the entire life cycle of a product or service. It is a product-based form of environmental auditing, that calculates the environmental burdens accompanying its existence [5].

LCA is becoming more widely adopted in the context of international environmental regulations, such as eco-labeling.

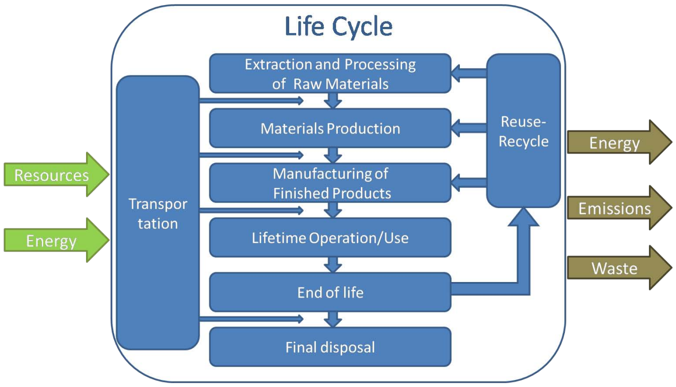

Fig. 3. Cradle-to-Grave Life Cycle

Additionally, it can be used for decision making during the product development and improvement procedure, since it can indicate components or areas in the manufacturing process that are more energy or carbon intensive. Consumers can refer to LCAs in order to compare the environmental behavior of products, while companies can use them in marketing campaigns.

Energy and carbon audit is especially important when renewable energy or efficient generation technologies are concerned. Although these devices usually have negligible emissions during their operation, the embedded energy and carbon in their materials are sometimes high, implying a long period for the device to generate the energy (and mitigate the carbon) needed for its manufacturing. Detailed Life Cycle Assessments (LCA) can calculate the exact payback period, and help decision makers towards the correct choices. Additionally when applied on energy systems an LCA includes indicators for energy and carbon intensity (kJ/kWh, g CO_2/kWh), energy and carbon payback period (months) and energy return on energy invested (multiples).

C. *Study Process*

In order to estimate the energy and carbon associated with the entire life cycle of the device, the study has been divided into five discrete phases:

1) **material weight breakdown**, where all the materials included in the device are identified and quantified by weight
2) **material embodied energy/carbon**, where the embodied energy and carbon of each material (including their machining operations) are estimated
3) **assembly and transport**, where all the final manufacture operations and transport to the operation site are assessed
4) **operation**, where the overall energy and carbon inputs and outputs associated with the operational life are calculated
5) **end of life**, where all the decommissioning operations are considered, including recycling and final disposal.

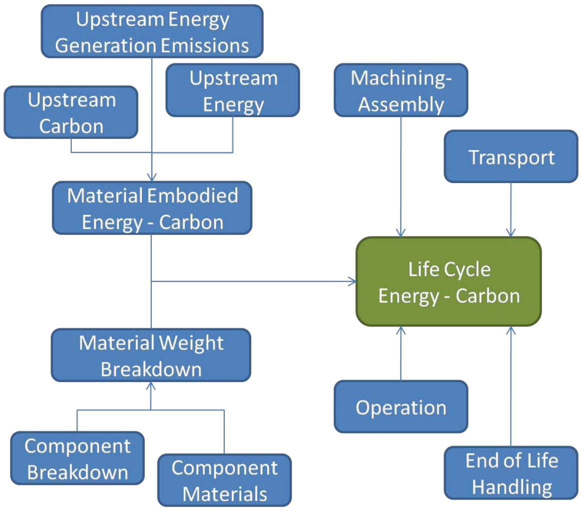

Fig. 4. Study Process

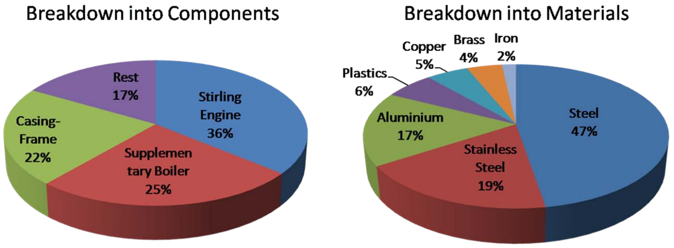

Fig. 5. Breakdown into Components and Materials

III. LIFE-CYCLE ENERGY AND CARBON ANALYSIS

The total energy consumption and carbon emissions associated with the micro-CHP are the aggregate values across its life cycle. This includes the materials comprising its components, manufacture and commissioning operations, gas consumed throughout its operational life, decommissioning and end-of-life handling. In this section the entire embodied energy and carbon is calculated, according to the study process.

A. *Materials Breakdown*

Using publicly available specification manuals, data sheets, Life-Cycle Assessments on condensing boilers with similar thermal outputs, data sheets of boilers and various CHP systems published by several manufacturers, extensive research in the international bibliography and contacts with the manufacturers, the preliminary breakdown of the device into its components and materials was possible, and is summarized in Table I and Figure 5.

B. *Materials Embodied Energy and Carbon*

For the calculation of the embodied energy and carbon of the raw materials contained in the device, the UK-oriented Inventory of Carbon and Energy (version 1.6a) has been used [6]. The information contained in the inventory was collected from secondary sources in the public domain, including journal articles, LCAs and books. UK data have been preferred but, when not available, European average data have been

TABLE I
DEVICE BREAKDOWN INTO COMPONENTS AND MATERIALS

Component	Material	Weight (kg)
Generator Casing	Generic Steel	8
External Springs & Frame	Generic Steel	8
Heater Head	Stainless Steel	8
Displacer	Stainless Steel	5
Piston	Aluminium	3
Planar Spring	Stainless Steel	2
Engine Burner	Stainless Steel	2
Permanent Magnets	Iron-Neodymium	2
Alternator Coil	Copper	2
Engine Flange	Copper	1
Heat Exchanger	Aluminium	11
Air-Gas Supply and Valves	Generic Steel	8
Hydraulics	Brass	3
Burner	Stainless Steel	2
Rest of Boiler	Generic Steel	2
	Stainless Steel	2
	Copper	1
Casing and Frame	Generic Steel	20
Wall Plate	Generic Steel	5
Fan	Polypropylene	2
Plastics (Rest)	Polypropylene	5
Inner Flue Duct	Aluminium	2
Rest	Generic Steel	3
	Aluminium	3
	Copper	2
	Brass	2

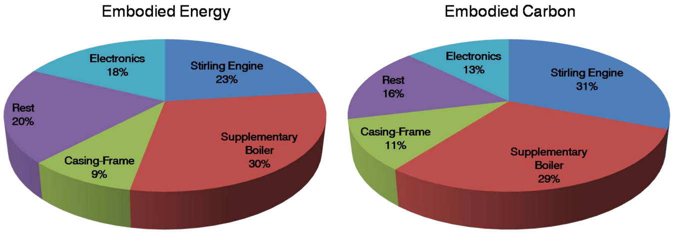

Fig. 6. Contribution of Components to the Embodied Energy and Carbon

used. The boundary condition of the coefficients presented in the inventory is cradle-to-gate. This approach includes all the energy and carbon associated with the material until the product leaves the factory gate, including the principal manufacturing processes like extrusions and castings. Post processing procedures like machining, forging and joining are not included, and their energy and carbon intensity is studied in the next paragraph.

Figures 6 and 7 show the respective breakdowns of embodied energy and carbon by component and by material The Stirling engine is seen to contribute significantly, with only the supplementary boiler having a large impact. In terms of materials, aluminum has the largest contribution overall despite not being the dominant material by weight.

C. Machining, Assembly and Installation

The energy requirements of the manufacturing processes have been calculated based on the specific-energy intensity of basic machining operations [7]. Additionally, based on the carbon intensity of the grid electricity in the UK [8], the emissions of these operations have been estimated.

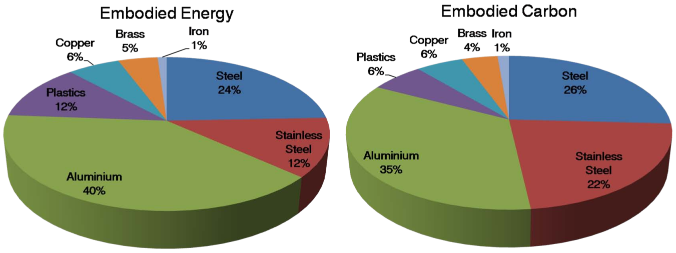

Fig. 7. Contribution of Materials to the Embodied Energy and Carbon

D. Transport

Most of the micro-CHP device components, are manufactured in the UK. As no information on manufacturing and assembly locations were made available by the manufacturer, these were assumed based on extensive research on locations where similar boilers and engines are constructed.

For the calculation of the energy and carbon intensity of the transportation of the various components and of the final device to the operation site, the coefficients for fuels suggested by Defra and DECC [8] have been used. It has also assumed that the upstream energy and carbon requirements of the fuels are 20% of their final calorific value.

E. Operation and Maintenance

Energy consumption and carbon emissions continue to occur throughout the operational life of the micro-CHP device. According to the manufacturer, the average annual gas consumption of the device, as measured in real case studies, is 26.48 MWh. Additionally, the electrical power consumption has been calculated at 409.5 kWh per year. However, due to proximity to the generator, this power is assumed to be supplied by the device rather than the grid. Therefore, it has no environmental impact, it just reduces the power generation trends of the device.

The carbon coefficient of natural gas on a gross calorific value basis is 0.18358 kgCO$_2$/kWh, while the upstream energy and carbon intensity of the production and delivery of the gas is 0.396 MJ/kWh and 0.03996 kgCO$_2$/kWh [8].

As far as the maintenance procedures are concerned, the manufacturer estimates that only one yearly inspection will be needed.

F. End of Life Handling

Although none of the existing devices has reached its end of operational life, a handling similar to that of heating boilers is assumed. The device is removed from the property and returned to a scrapping plant, where it is dismantled and the extracted materials are either recycled or disposed. Since no information on the end-of-life was available, UK mean values have been used, while the waste handling is not quantified due to lack of relevant data.

Throughout this project, an open-loop recycling procedure has been assumed. According to this approach, recycling processes take place not only after the disposal of the product, but before its manufacture as well. Consequently, both recycled

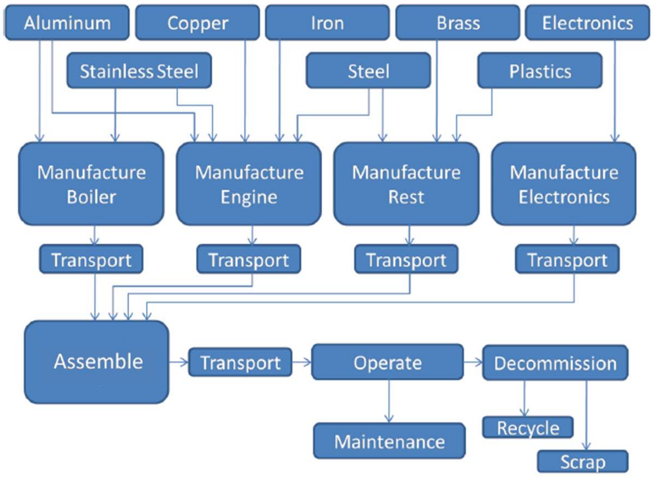

Fig. 8. Life Cycle of the micro-CHP Device

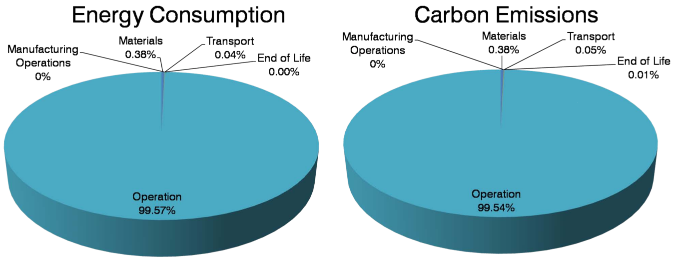

Fig. 9. Contribution of Life-Cycle Phases to the Embodied Energy and Carbon

materials in the manufacture and recyclable materials after the disposal should be taken into consideration in the calculation of the environmental burden associated with the product.

IV. TOTAL EMBODIED ENERGY AND CARBON

After quantifying the contribution of all these components, the total embodied energy and carbon were calculated and are summarized in Table II. Embodied energy and carbon are approximately 1600 GJ and 90 tonnes CO_2over the life cycle.

Figure 9 shows that the operational phase, specifically the burning of natural gas contributes to over 99% of these figures. This leads to almost linear relationship between energy consumption (carbon emissions) and operational life, or annual generation. Consequently, unlike renewable energy devices with high ratio of embodied to operational energy and carbon, the micro-CHP devices's environmental behavior per generated unit does not depend on its generation trends. Higher generation may imply higher overall savings, but does not imply lower emissions per thermal or electrical kWh.

V. ENERGY AND CARBON SAVINGS

The environmental burden of a product relates to the energy consumption and carbon emissions of its entire life-cycle. In the case of power generators this burden is normalized to a functional unit that is usually the electrical energy generation (kWh_{el}). This straightforward calculation is not possible in the case of CHP, as there are two products. In such a system a complex consideration of both heat and power generation is essential. In this analysis the method of evaluating the avoided burden is used, where the performance of the micro-CHP device is estimated by the benefits gained by substituting conventional production of heat and electricity from the grid.

TABLE II
EMBODIED ENERGY AND CARBON OF LIFE-CYCLE PHASES

	Em. Energy (MJ)	**Em. Carbon** (kg CO_2)
Raw Materials:		
Non-recyclable	629	22
Recyclable (No Recycling)	7791-8932	523-570
Recyclable (40% Recycling)	6279-7192	424-461
Electronics	1509	64
Operations:		
Machining	32-91	5-14
Assembly	11	2
Transport:		
Sea	158	12
Air	32	2
Road	509	35
Operational Life:		
Gas Consumption	1587211	88790
Maintenance	6899	482
End of Life:		
No Recycling	-	-
Average Recycling (Savings)	2812-3056	192-197
Transport	139	10
Dismantling	11	2
Total:		
No Recycling	1604931-1606132	89948-90003
UK Average Recycling	1600607-1601276	89652-89684

The energy and carbon savings from substituting the best performing conventional condensing boiler and electricity from the grid with the micro-CHP system, have been calculated at 4922 to 5118 MJ/year and 523 to 543 $kgCO_2$/year respectively.

The payback period for a power device is the operational time needed by the device to compensate for its embodied energy and carbon. In the case of devices operating on fossil fuels, the embodied energy of their operational life is never paid back, since they always produce less energy than they consume. In these cases, the payback period can refer to the entire life-cycle energy and carbon, excluding the operational phase. Assuming the average UK recycling rate for the device's materials the embodied energy is paid back in 1.32 years while the embodied carbon in 0.75 years. Assuming no recycling these values are 2.32 years and 1.35 years respectively.

VI. CONCLUSION

Concerns about climate change that might be anthropogenic have been growing over the last decades. Increased environmental awareness has created the necessity of standardized and objective evaluation of the environmental performance of several products and devices. Especially in the case of power generation devices, energy and carbon auditing is substantial for decision making in the context of a sustainable future strategy.

Microgeneration has been promoted as a means of lowering carbon emissions by decentralizing the established power generation regime. Combined heat and power generation in particular is thought to provide the highest benefits, since it makes use of the power and heat co-product to achieve high efficiency rates. Although large scale cogeneration has been used for many years, and its environmental benefits have been proved, small-scale domestic microcogeneration is feared to have low efficiencies, due to the loss of economies of scale, that relate not only to cost but also to delivered energy and carbon savings.

The device investigated in this study is the first wall-hung micro CHP system commercially available throughout Europe. It can cover all the needs of an average household for space heating and hot water while generating power, delivering up to 1 kW of power and 24 kW of heat. Assuming an operational life of 15 years and an annual heat generation of 20 MWh, the life-cycle energy consumption and carbon emissions associated with the device have been calculated at 1605-1606 GJ and 90 tonnes CO_2 respectively. If average UK recycling rates are assumed for post-decommissioning handling and 40% of secondary materials involved in the manufacture phase, then these figures are recalculated at 1601 GJ and 89.7 tonnes CO_2 respectively. The vast majority of the energy consumption and carbon emissions are associated with the burning of natural gas during the operational phase of the device.

Assuming that this device replaces the best available gas-powered condensing boiler and electricity from the grid, and taking into consideration current gas and electricity energy and carbon intensity values, the energy and carbon savings achieved by the micro CHP device are 4922 to 5118MJ/year and 523 to 543 kg CO_2/year respectively. The lower values are achieved when average recycling rates are considered.

Much higher benefits could be potentially achieved if the system is powered by less energy and carbon intensive fuels, like renewable biogas. Additionally, its environmental behavior could improve by increasing the delivered power-to-heat ratio, for example, by improving the efficiency of its Stirling engine or using an alternative method to generate electricity. Potential improvements on the embodied energy and carbon of the components comprising the device (e.g. increasing the recycling ratio or using less intensive materials) would improve its energetic performance, but only slightly.

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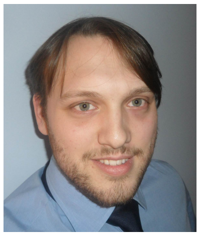

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