Energy generation potential of anaerobic digestion from the food and farming wastes of the UK food chain

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Abstract

The UK food chain was responsible for 18% of the total UK energy use and produced 32% of the country's greenhouse gas (GHG) emissions in 2011. The holistic food chain is estimated to produce around 15Mt of post-farm gate food waste, corresponding to 15% of overall food purchases. The UK Waste and Resources Action Programme (WRAP) estimates that post-farm gate food waste is responsible for more than $20MtCO_2e$ emissions, making 12% of total direct food chain emissions. The majority of post-farm gate food waste comes from households (7.2Mt) and the manufacturing sector (3.2Mt). This waste is largely disposed to landfill. The agricultural sector was found to account for approximately 90Mt of organic material waste, mostly in the form of manures and slurries. In addition to contributing to GHG emissions, wastes also depict a financial and resource flow weakness in the economy. As a result, the UK government is actively promoting energy recovery from waste, particularly through Anaerobic Digestion (AD) systems. This paper explores the energy generation potential of food-chain wastes (i.e. food and manure/slurry wastes) employed in AD systems to produce biogas, which is in turn used in combinations of Combined Heat and Power (CHP) and Organic Rankine Cycle (ORC) systems to generate power. Future scenarios on the amount of wastes are developed, and the relative potential of the technologies are investigated. The addition of ORC system with conventional CHP systems have shown to increase the electricity generation potential, at the expense of heat generation. The impacts of the implementation of these technologies are determined from observable trends in the literature, and are intended to be illustrative rather than predictive. For the case of this paper, the 'Gas Turbine CHP with High-Grade ORC' has shown the highest energy generation potential upto 2050 for the UK economy.

Keywords: Food chain wastes, anaerobic digestion systems, renewable energy technology, biogas

Introduction

The Food and Agriculture Organisation of the United Nations (FAO) has expressed concerns over the high dependence of the global food sector on fossil fuels, which are not aided by the projected 70% increase in current food consumption by 2050 due to the rise in global population [1]. Developed economies use the majority of energy in processing and distribution operations, while developing countries use energy mainly for retail, preparation and cooking [1]. This heavy reliance on fossil-fuels has reinforced the concept of the Energy-Food-Climate Nexus and the importance of food security [1], where all three aspects (Energy, Food and Climate) are intricately linked, such that actions taken in one area are very likely to have consequences on the other areas. It is therefore important to

tackle the nexus from both the demand and supply perspectives, that is; improving resource efficiency in the supply chain as well as adopt more sustainable consumption behaviour (such as minimising waste and consuming seasonal products).

Food has been found to provide a high degree of personal choice, therefore providing a unique opportunity for consumers to lower their personal impacts [2]. The UK food chain was responsible for 18% of the national energy consumption, and produced 32% of greenhouse gas (GHG) emissions in 2011 [3,4]. The food chain in the UK consists of various sectors, generally divided under the Standard Industry Classification (SIC) codes 10 and 11 [5], extend from food products (meat, fish, bakery, dairy, etc.) to alcoholic and soft drinks. Energy is used at various stages of each food sector's chain; to farm, manufacture, process, distribute, retail

and to consume food. Hence, the energy gradually embeds in the intermediate and final food products, whereby any food products not consumed by the chain therefore represent a loss of embedded energy and a waste of resources. In 2011, total UK food wastes amounted to 15 Mt, with approximately 50% arising from the production, manufacturing and retail sectors, and the rest from the household and hospitality sectors [6]. However, 6 Mt is avoidable waste arising due to food/drinks being thrown away untouched, excess production, personal preference, or accidents [6]. This can be minimised/ avoided through changes in food labelling and consumer behaviour, a relaxation of quality standards, improved manufacturing processes and logistics and better temperature control [7].

Unavoidable waste from the food chain arises from both organic food wastes (9Mt) and packaging wastes (10Mt) [6]. Packaging wastes can be reduced through increased recycling, re-use and avoiding packaging [8], whilst unavoidable organic waste is produced from food remnants that cannot be ingested by humans or the by-products of farming. In an attempt to better manage waste, the EC Waste Framework Directive 2008/98/EC established the waste hierarchy shown in **Figure 1**.
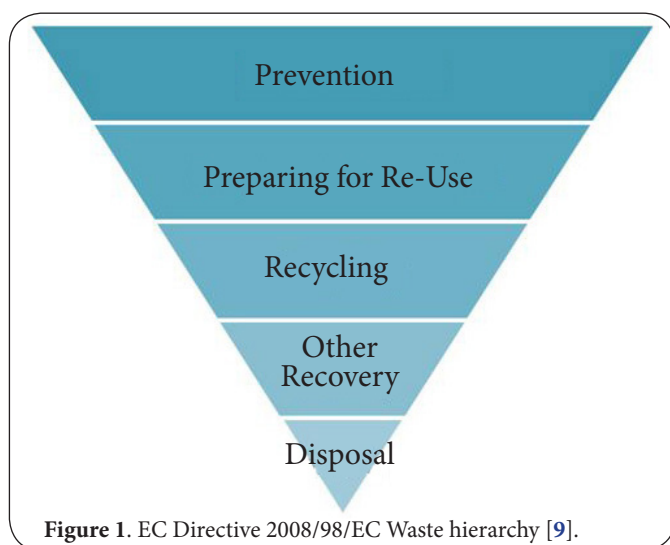
Figure 1. EC Directive 2008/98/EC Waste hierarchy [9].

For the purpose of this paper, the emphasis will be on the 'other recovery' section of the waste hierarchy which includes the recuperation of embedded energy in organic wastes, i.e., improving the resource efficiency of the food chain. Organic food wastes and agricultural wastes, such as cattle/pig slurries and manures (estimated to be 90Mt/year [8]) can effectively be used as an energy resource in different stages of the food chain. A popular method is anaerobic digestion (AD), which uses microorganisms to convert organic waste into methane-rich biogas (used in the generation of electricity and heat) and biofertiliser in the absence of oxygen. AD systems have been strongly favoured and advocated by the UK government, especially through the UK renewable energy incentives, as

a mean to divert waste from landfills and encourage a more efficient resource flow across the economy [10]. The general AD process schematic is shown in **Figure 2**.
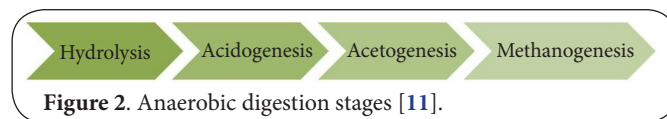
Figure 2. Anaerobic digestion stages [11].

Different strains of bacteria are used to digest the complex carbohydrates, lipids and proteins in food into their component parts in the *hydrolysis* phase, which are then converted to carbonic, volatile fatty acids and alcohol in the *acidogenesis* phase. These products are then converted to acetic acid in the *acetogenesis* phase, before being converted to methane (CH_4) in the *methanogenesis* phase. Biogas generally consists of 50-75% CH_4 and 25-50% CO_2, with traces of other gases [12]. AD systems are generally divided into mesophilic (operating temperatures of 25-45°C) and thermophilic (operating temperatures of 50-60°C). The latter has a faster biogas production rate, but mesophilic systems are more common in the UK due to lower capital and operating costs [13], as well as the relatively more stable operation for food waste [11].

In the UK, regulations on food waste collections are not universal. In England, only 26% of municipal councils provide separate food collections whereas this percentage is 95% in Wales, while Scotland now imposes local councils to separately collect food wastes [14]. Source-segregated food wastes (i.e., separating organic food from inorganic wastes in municipal solid waste (MSW) basket) are being preferred due to: high energy costs of processing wet waste with AD; EU regulations in various countries preventing the use of digestate produced from inorganic materials [15]; and the possible higher biogas yield, depending on the composition of MSW. For the purpose of this study, due to the difficulty in quantifying the composition of food waste within the UK economy [16], the quantities reported in references [15,17] are adopted. Furthermore, food waste only refers to the organic section of waste.

Currently, 35% of household and hospitality food waste is landfilled, whilst 7% is sent to AD–although this amount is growing [14]–whilst, the grocery supply chain (i.e., retail, wholesale and manufacturing) sectors send approximately 10% and 5% of food wastes to landfill and AD, respectively [16]. Anaerobic digestion technologies produce the fuel (biogas), an alternative to fossil fuels, but require energy conversion technologies to generate useful energy. This paper addresses the technologies used to generate electricity and heat from AD plants. It will provide a description of the general performance of each technology, and will employ a series of scenarios to determine the future energy generation potential of biogas produced from food-chain wastes in AD plants. This is considered important in order to address energy security issues and the impact of incorporating further renewable

energy technologies in the UK economy to satisfy the greenhouse gas (GHG) emission targets outlined in the Climate Change Act 2008.

Material and methods
Energy conversion technologies
This section describes the two most popular methods of generating electricity and useful heat from biogas generated from AD plants. These consist of Combined Heat and Power, and Organic Rankine Cycle.

Combined heat and power (CHP) systems
Conventional CHP systems are characterised by their ability to generate electricity and to recover the heat that would otherwise be wasted from electricity-only generation. The potential can be further extended to include cooling, through the use of absorption chillers, making an overall tri-generation system. The use of CHP reduces overall fuel consumption and greenhouse gas (GHG) emissions, as well as improves the overall efficiency of converting fuel to useful energy. CHP plants producing electricity and heat from biogas generated from AD systems are currently supported by both the Renewable Obligations (RO) and Renewable Heat Incentive (RHI) schemes in the UK, and are therefore expected to considerably increase in amount in the future [18]. The general schematic for electricity and heat generation from CHP plants, using an AD system, is shown in **Figure 3**.
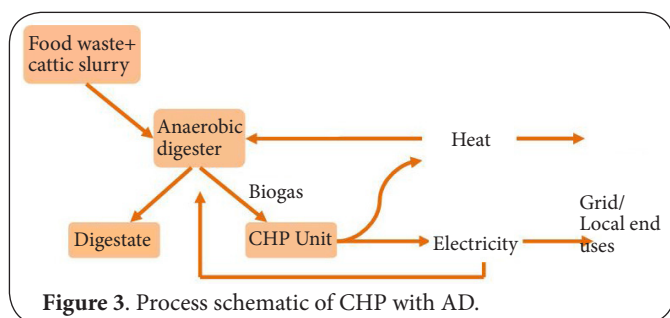

Figure 3. Process schematic of CHP with AD.

Generally, the low-grade heat produced by CHP units is primarily re-used in the digester, while the rest of the heat can be used for other processes or district heating [4]. Gas turbine, reciprocating engine and steam turbine CHP systems can all employ biogas to generate useful energy, with similar overall efficiencies in the region of 70-80% [19], but different heat to power ratio. Reciprocating engine CHP systems tend to have a heat-to-power ratio of 1.3:1 (with low grade (LG) output heat), gas turbine CHP systems have 2.5:11 (with high grade (HG) output heat), and steam turbine CHP systems generally have a ratio of 10:11 (with low grade output heat), using 60% methane biogas [20].

Organic rankine cycle (ORC) systems
An ORC system is based on the similar working principles as steam turbines, but with a working fluid which has a higher or lower boiling temperature compared to water [20]. The choice of the working fluid is dependent on the grade of heat being supplied to the system, which produces a relatively versatile system, which can either employ heat from boilers or waste-heat from conventional CHP systems. The process schematic of heat and electricity generation using ORC with an AD plant is shown in **Figure 4**.
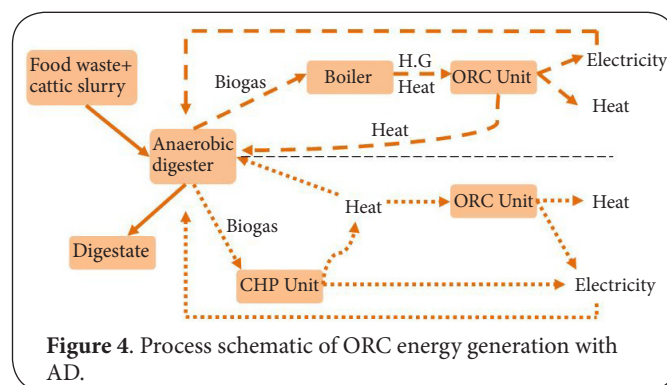

Figure 4. Process schematic of ORC energy generation with AD.

The use of ORC can take two general pathways. The first is a boiler driven stand-alone ORC system where the high temperature working fluid (such as oil) employs high-grade (H.G) heat to produce electricity and lower grade heat. The alternative is to use low grade waste heat from CHP systems to feed into a low-temperature working fluid ORC system. In this case, only useful electricity can be produced from the ORC, as the heat is of too low quality to be of use [20]. The latter pathway can also employ high temperature exhaust gas from gas-turbine CHP systems, which would then require a high boiling temperature working fluid, and hence produce a more useful end-heat.

High-grade heat ORC systems typically have high efficiencies (~98%), disaggregated into 18-24% for gross electric power and 74-80% of thermal power to heat users, with minimal thermal and electric generator losses. Nonetheless, the overall efficiency also includes the boiler efficiency of 83-88% [21]. Low-grade heat ORC systems typically have lower electrical efficiencies in the range 5-10%, whilst the heat condensed from ORC systems are generally of too low grade to be of any use [22].

Energy generation scenarios
The main driver for the energy generation potential of AD systems is the amount of food and farming wastes generated by the food chain. Food wastes in the chain consist of both the supply-chain and household/hospitality wastes, with an approximate 50% ratio, and as described by the waste hierarchy in **Figure 1**, the first method in managing waste is prevention. In this regard, the UK is bound by the Courtauld Commitment which places short term targets on the supply-

chain and household sectors of the food chain to reduce food wastes. At the EU level however, the food waste reduction target is set at 50% by 2020, relative to a 2010 level, as set by the European Commission target [23]. The prediction performed in this paper assumes a constant product mix in the predictions for the post-farm gate food chain, and therefore considers the overall food wastes as opposed to specific-food product waste. Regarding farming wastes, the main driver for biogas production from cattle and pig slurries is based on population growth and the demand for farming products. It has been estimated that 90Mt of manure and slurries is currently generated annually by the farming industry [8].

The projections made in this paper are until 2050, where missing values for specific intermediate periods are linearly interpolated. Food waste targets in the food chain are currently dictated by the Courtauld Commitment, which is currently under phase 3 (2012-2015). Hence, the additional targets from 2015-2050 are extrapolated assuming a constant rate of change of successive years. Agricultural wastes are determined according to the UK population growths and relative change in consumption of meat and dairy products, predicted by the Food and Agriculture Organisation (FAO) [24]. The quantity of slurry and manure is then linearly adjusted according to the relative change from 2000, where the total amount of manure and slurry is taken to be 90Mt. The projections in food and agricultural wastes are shown in **Figure 5**. It should be noted that wastewater sludge generated as a by-product of processing food, such as dairy products [25], is not considered in this study.

Figure 5. Projected food and agricultural waste in the UK food chain.
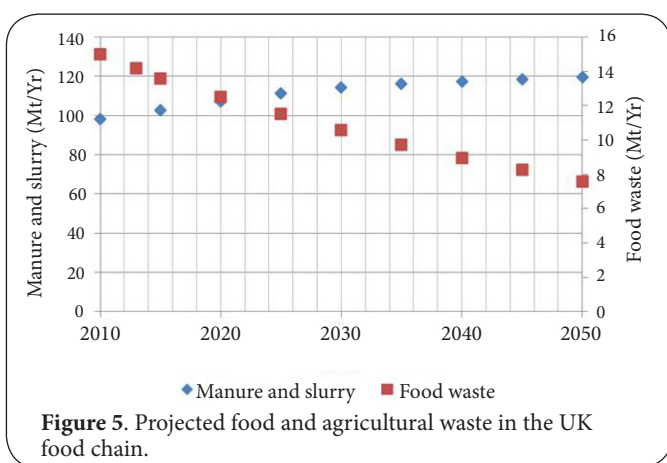
The nominal production of biogas from cattle (including sheep and poultry) and pig manure and slurry is estimated at 28.8 m³/tonnes of manure [26] based on the relative weight of carcass produced in the UK, whilst food biogas is estimated to be at a rate of 97 m³/tonnes of food waste for the UK [15,17]. The amount of energy required by mesophilic digesters is estimated to be 0.01% and 7% of heat and electricity, respectively, relative to the amount of embedded

energy in the produced biogas [11]. As mentioned previously, only 7% of household and 5% of supply-chain food waste are currently sent to AD; whilst approximately 0.1% of farms employ AD [27].

In this regard, different scenarios will incorporate different proportion of AD system in the food chain. The different scenarios are shown in **Table 1**.

Table 1. Scenarios with different relative adoption of AD systems for the UK food chain waste.

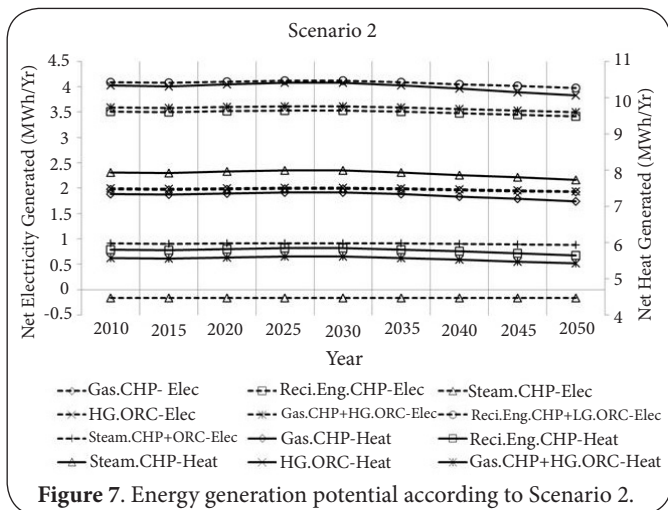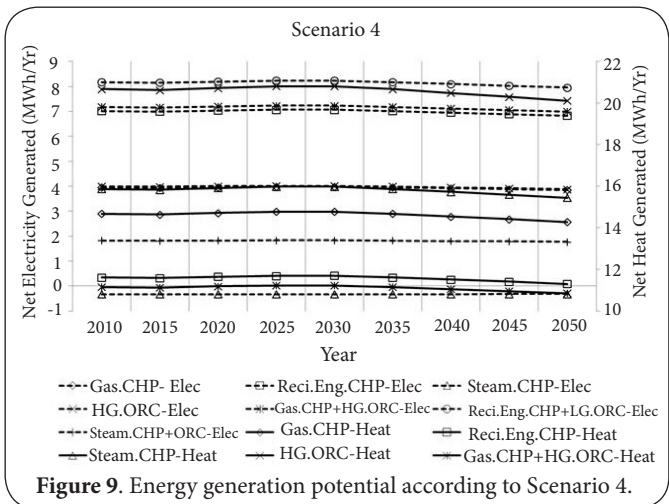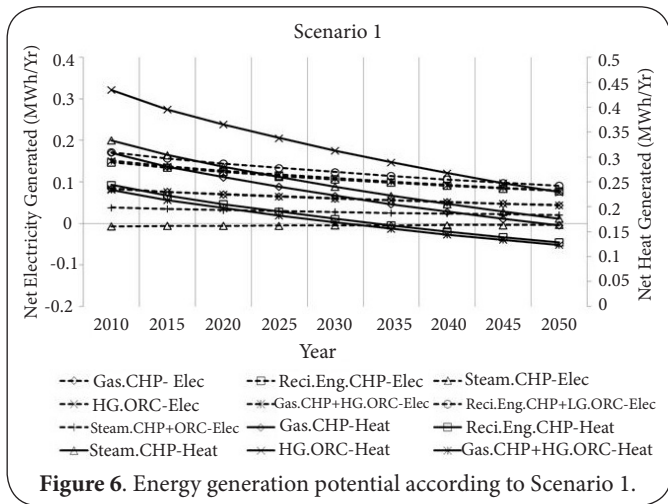| Scenario No.	% of food waste from supply-chain to AD	% of food waste from Households to AD	% of farms using manure and slurry in AD
1	5	7	0.1
2	50	50	50
3	50	50	100
4	100	100	100
5	Progressive change in scenario from No.1 in 2010 to No.4 in 2050		

Scenario 1 refers to the current employment of AD systems and assumes that the relative amount of wastes going to AD stays at the same current level. Scenarios 2 assumes an overall increase in the amount of waste going to AD, whilst scenario 3 provides a doubling in the amount of manure and slurry that goes to AD, relative to scenario 2. Scenario 4 provides with the ideal case scenario where all wastes generated by the supply-chain, household and farms go to AD systems to produce biogas. The progressive scenario 5 considers the linear implementation of AD systems in the food chain, from scenario 1 to scenario 4.

The respective performances of the different systems depicted in section 2 are therefore evaluated according to these scenarios.

Results and discussion

The respective performances of the energy generation systems when employed with AD system are shown in **Figures 6-9** below. The net aggregated energy is divided into electricity and heat, and accounts for the energy consumed by the AD system when operated with the energy generation system.

Figures 6-9 show that the relative performances of each system for the same scenario are similar. For electricity generation, the 'Reciprocating engine CHP with Low Grade CHP' has the highest performance, followed by the 'Gas Turbine CHP with High Grade ORC'; the Reciprocating Engine CHP; High Grade ORC; Gas Turbine CHP; 'Steam Engine CHP with Low grade ORC'; and lastly the Steam Engine CHP. Regarding heat generation, the high grade ORC has the high performance, followed by the Steam Engine CHP; Reciprocating Engine CHP; and the Gas Turbine CHP with High Grade ORC. Owing to the heat-power ratio of the different CHP systems and the ORC, favouring heat production (as mentioned in section 2),

Figure 6. Energy generation potential according to Scenario 1.

Figure 7. Energy generation potential according to Scenario 2.

Figure 8. Energy generation potential according to Scenario 3.

Figure 9. Energy generation potential according to Scenario 4.

The negative electricity values obtained for the Steam Engine CHP when employed in combination with an AD system are due to the fact that the electricity produced by the CHP is lower than the electricity consumed by the AD system. Hence, for this particular combination of system, additional electricity will have to be purchased in order to run the overall system. In most scenarios, the balance of waste between the waste increase from manure/slurry and the reduction in food chain waste due to the Courtauld Commitment (refer to **Figure 5**) causes an overall reduction in the aggregated heat and electricity generated over time. However, scenario 3 which assumes a relatively higher increase in manure/slurry compared to food wastes, show an increase in both the heat and electricity generated for all systems from 2010 to 2030. A similar situation is observed from scenario 4, where the rate of reduction in energy generated increases after 2030 due to stagnating effects of the increase in manure/slurry, as opposed to the reduction in food wastes. **Figures 6-9** show that the energy potential of AD systems is dependent on the energy conversion technology and the amount of waste/biogas produced from the food chain.
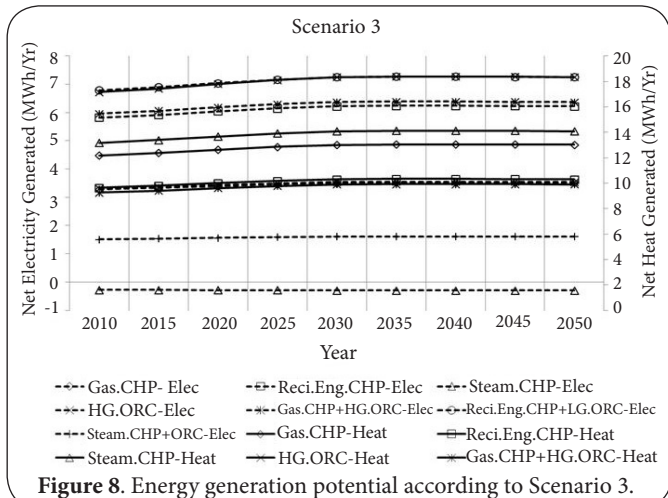
The progressive scenario shown in **Figure 10** shows the energy generation potential of AD if its implementation is linear from scenario 1 in 2010 to scenario 4 in 2050. The detailed energy results are tabulated in **Table 2**.

If the implementation of AD varies according to scenario 5, i.e., starting from the current level of adoption to all food-chain wastes being processed by AD systems in 2050, the trends are expected to vary according to **Figure 10** and **Table 2**. All technologies produce more heat than electricity, and the relative increase in total power generated of all technologies is approximately 4500%, from 2010 to 2050. The H.G ORC is able to generate the highest possible power in 2050, relative to the other technologies, however the majority of the energy is in the form of heat as shown in **Table 2**. Conversely, the Steam CHP with LG ORC generates the lowest power in 2050, where all the power is electricity. It is also observed that the

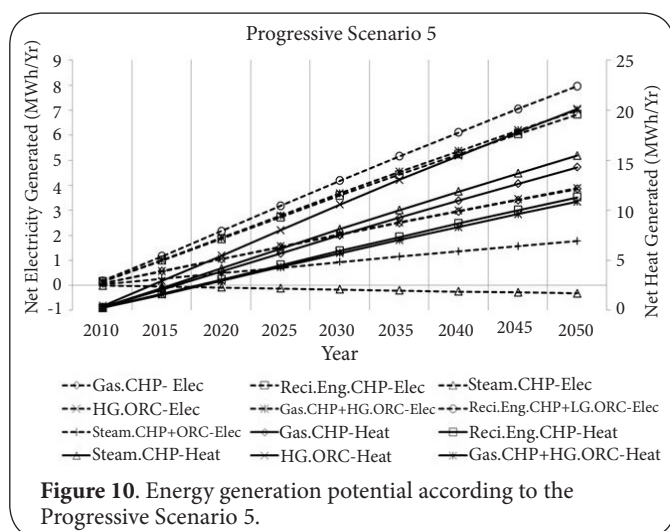the relative heat generated by the systems is higher than the electricity generated.

Figure 10. Energy generation potential according to the Progressive Scenario 5.

Table 2. Energy generation potential with progressive scenario 5.

Progressive scenario 5						
Technology	Heat generated (MWh)		Electricity generated (MWh)		Total energy generates (MWh)	
	2010	2050	2010	2050	2010	2050
Gas CHP	0.31	14.28	0.08	3.85	0.39	18.13
Reci.CHP	0.24	11.30	0.15	6.83	0.39	18.13
Steam CHP	0.33	15.45	-0.01	-0.31	0.33	15.13
H.G ORC	0.44	20.11	0.08	3.88	0.52	23.99
Gas CHP+HG ORC	0.00	0.00	0.17	7.96	0.17	7.96
Steam CHP+LG ORC	0.00	0.00	0.04	1.77	0.04	1.77

addition of ORC to the CHP systems results in a reduction of the total power generated, with however a relative increase in the electricity generated compared to the CHP systems without ORC. Furthermore, adding the ORC to the Steam Engine CHP actually generates electricity, as opposed to only consuming electricity, as in the case of the Steam Engine CHP only. Hence, the main impact of the ORC system is to divert a portion of the energy content of the biogas from generating heat to generating electricity. Hence, based only on the energetic analysis of the power generation potential of the different technologies, the choice of a specific technology depends on the type of energy (heat or electricity) required by the economy.

Conclusions

Food-chain waste is split into i) food waste generated by the food chain and ii) manure/slurry produced during primary production processes in farming. The future trends for food waste are determined according to the Courtauld Commitment, whilst the amount of manure/slurry produced in the UK economy is determined according to population growth and

projected product mix. The paper showed that the power generation potential of food chain wastes is relative to the amount of biogas generated from waste and the respective technology employed. Different scenarios were investigated based on the amount of waste sent to AD systems. The higher implementation of AD increases production of biogas and therefore power generated, but the relative increase in power generated depends on the individual technologies. Furthermore, for the same scenario, the reduction in food wastes has a dominating influence on the overall trend of biogas production, relative to the increase of manure waste. Regarding the technologies; employing a system consisting of HG ORC using all food-chain wastes generated in the UK food chain, generates the highest power in 2050, with a relative increase of 4500% compared to the current use of AD with the same technology. It was also observed that the addition of ORC with conventional CHP systems is beneficial for electricity generation, but with a reduction in heat produced. The trends in this paper are aimed to be illustrative rather than predictive, and a more complete evaluation of the performance of these technologies should also consider costs and greenhouse gas emissions, which will be the focus of further studies.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

Authors' contributions	BLG	SAT
Research concept and design	✓	✓
Collection and/or assembly of data	✓	✓
Data analysis and interpretation	✓	✓
Writing the article	✓	✓
Critical revision of the article	✓	✓
Final approval of article	✓	✓
Statistical analysis	✓	✓

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