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Renewable and Sustainable Energy Reviews

Waste-to-energy conversion technologies in the UK: processes and barriers – a review

--Manuscript Draft--

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Abstract:	This paper reviews the sector of waste-to-energy looking at the main processes and feedstock involved. Within this, incineration, gasification, pyrolysis, anaerobic digestion and hydrothermal liquefaction are named and discussed. Through the discussions and scrutiny, manure is highlighted as a significant source of ammonia, methane, and nitrogen oxides emission, estimated to be 40%, 22.5% and 28% respectively of the total UK's anthropogenic emissions. Manure, and indeed the pollution it poses, are shown to remain largely ignored. In waste to energy processing, manure is capable of providing biogas for a number of pathways including electricity generation. Anaerobic digestion is highlighted as a suitable process with the crucial capability of drastically reducing the pollution potential of manure and slurry compared to no processing, with up to 90% reduction in methane and 50% reduction in nitrogen oxide emissions. If the majority of the 90 million tonnes of manure and slurry in the UK were to be processed through biogas harvesting, this could have the potential of producing more than 1.615 TWh of electricity. As such, the economics and legislation surrounding the implementation of anaerobic digestion for manure and slurry are discussed. In the end, restraining factors that limit the implementation of anaerobic digesters on farms in the UK are discussed. These are found to be mainly capital costs, lack of grants, insufficiently high tariff systems, rather than low gas yields from manure and slurry.
Response to Reviewers:	Reviewer #1: The authors have answered comments sufficiently and in great detail. I consider the revision of the text to be sufficient. However, I still have a few comments. 1) Check the section numbering, see "2.1 Biomass waste" and "2.1. Landfill mining". This has been corrected 2) Unify the units, see "Lower heating value (MJ/Kg)" in Tab. 3 vs "Higher heating value (HHV) (MJ/Kg)" in Tab. 4 etc. We didn't quite understand what reviewer wants us to do here. In Table 3 we have shown the Lower Heating Value (LHV) in MJ/kg and also the water content. In Table 4 we have shown the Higher Heating Value (HHV) in MJ/kg. The references for these values are also shown in these tables. These values were taken from the published sources where authors experimentally determined these values. If the reviewer wants

us to convert LHV to HHV or vice versa, we don’t believe this would be a correct approach as the Higher Heating Value (HHV) is calculated with the product of water being in liquid form while the Lower Heating Value (LHV) is calculated with the product of water being in vapor form.

3) Check the numbers format, e.g. Fig. 7 or Fig. 8 (b).

We didn’t quite understand what the reviewer is referring to here in Fig 7 or in Fig 8 (b). What numbers format do we have to check? The formats in both figures look good to us.

4) Check the format of the units, see P27 L20: "m3" vs "m^3".

This has been corrected

Reviewer #5: The revised version looks better. Some concerns:

1. The reviewer #1, #2 and #5 proposed a same question about this research's novelty. So please pay more attention to this question. I don't think the responses-to-reviewers and the new version solved this problem wonderfully.

The new version added some content in section 1 and proposed the value of this research. However, this manuscript mostly focus on what it intends to do, but didn't summarize the shortages of other reviews.

If what you want to do is based on these shortages, then it will make more sense.

We have added the summary of shortages of other reviews in the text.

2. The format needs to be unified based on the instruction of this journal, including the format of paragraphs and font size of tables. The authors should check it again, in particular in section 1, section 3 and section 4.

We have followed the guides for authors for this journal. Formats of paragraphs and font size of tables have been checked.

3. There are two 'section 2.1' in the clean version, which means that the following series-numbers of section 2 are incorrect.

This has been corrected

4. It will be better if Table 10 can be transferred into a line chart, which will show the trend clearly.

We believe that the Table 10 clearly represents the trend already. It shows the periodic change of tariffs from (Before 1 April 2016) and ends with (On or after 22 May 2018).

5. It is suggested to give its whole name at the first time use, for example p/kWh, do you mean pence for "p"? This research is faced to global researchers, so please provide specific explanations when essential. The authors should also check similar problems in the manuscript.

This has been corrected throughout the text.

Response to Reviewers R2

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This has been corrected

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This has been corrected throughout the text.

Waste-to-energy conversion technologies in the UK: processes and barriers – a review

William Foster[1], Ulugbek Azimov[1*], Paola Gauthier-Maradei[2], Liliana Castro Molano[2], Madeleine Combrinck[1], Jose Munoz[3], Jaime Jaimes Esteves[2], Luis Patino[1]

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Abstract: This paper reviews the sector of waste-to-energy looking at the main processes and feedstock involved. Within this, incineration, gasification, pyrolysis, anaerobic digestion and hydrothermal liquefaction are named and discussed. Through the discussions and scrutiny, manure is highlighted as a significant source of ammonia, methane, and nitrogen oxides emission, estimated to be 40%, 22.5% and 28% respectively of the total UK's anthropogenic emissions. Manure, and indeed the pollution it poses, are shown to remain largely ignored. In waste to energy processing, manure is capable of providing biogas for a number of pathways including electricity generation. Anaerobic digestion is highlighted as a suitable process with the crucial capability of drastically reducing the pollution potential of manure and slurry compared to no processing, with up to 90% reduction in methane and 50% reduction in nitrogen oxide emissions. If the majority of the 90 million tonnes of manure and slurry in the UK were to be processed through biogas harvesting, this could have the potential of producing more than 1.615 TWh of electricity. As such, the economics and legislation surrounding the implementation of anaerobic digestion for manure and slurry are discussed. In the end, restraining factors that limit the implementation of anaerobic digesters on farms in the UK are discussed. These are found to be mainly capital costs, lack of grants, insufficiently high tariff systems, rather than low gas yields from manure and slurry.

Keywords: waste feedstock; manure; anaerobic digestion; waste-to-energy

1. Introduction

The need to become more sustainable through the threat of global climate change and resource depletion is ever more prominent. Coupled with an ever-increasing population, rapid industrialisation, depleting fossil fuel resources present significant biowaste disposal and energy demand problems. In the UK, around 7.4 million tonnes of biodegradable municipal waste were sent to landfill in 2017 [1]. This waste could otherwise have been processed and recycled. The environmental impact of biodegradable waste extends beyond increasing greenhouse gasses due to the decomposition process. Untreated biodegradable waste release unpleasant odours due to decomposition and attracts scavenger animals and pests [2]. This has an impact on general public health and changes the biodiversity in the surrounding areas. Leaching from landfills not only contaminates the groundwater but can also affect the adjacent soil quality. In EU legislation, it is stipulated that biodegradable waste ending up at landfill must be reduced by 35% by 2020 compared to 1995 levels. This is one example of the driving forces behind waste to energy (WtE) processing, focused on reducing the volume of waste, recovering valuable products and producing electricity.

The term 'waste-to-energy' can be used interchangeably and encompass a variety of processes and technologies. The conversion of waste into energy will be analysed in this paper by the following processes: incineration, gasification, pyrolysis, anaerobic digestion, and hydrothermal liquefaction. The schematics of waste to energy processes are shown in Figure 1.

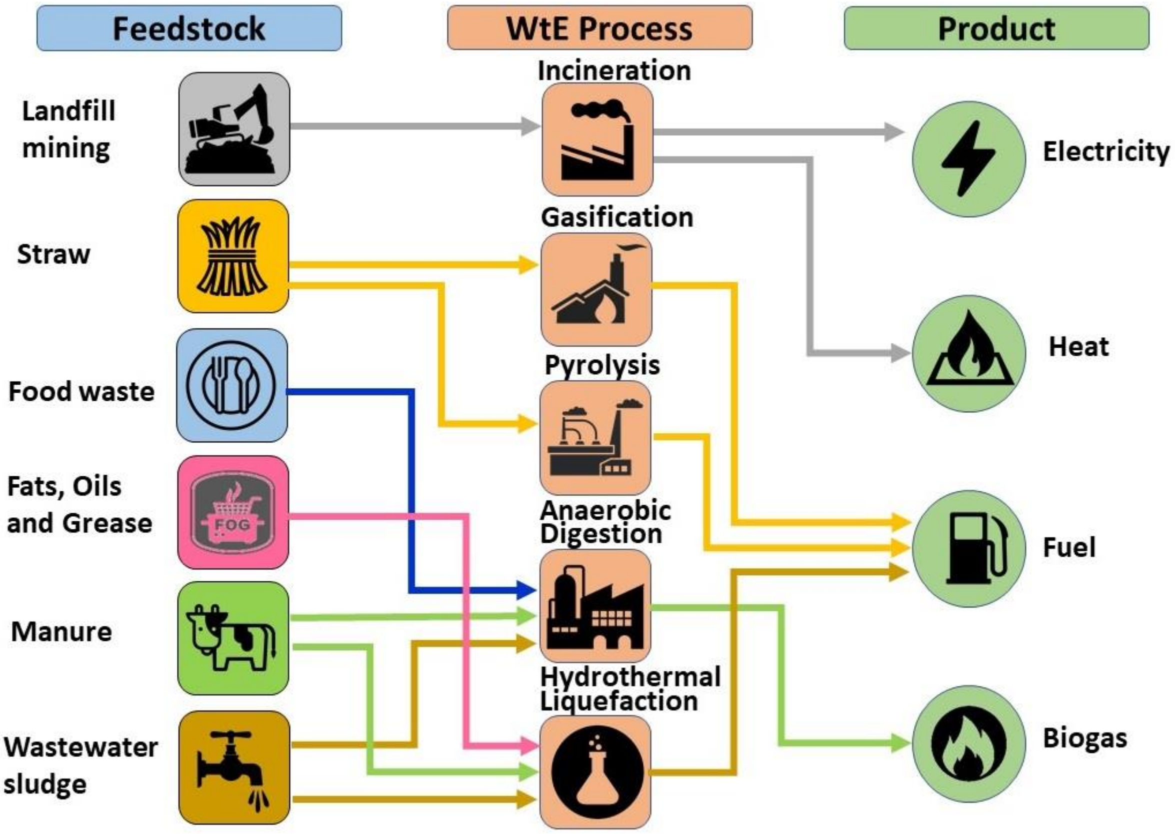


Figure 1. Schematics of waste-to-energy processes

Incineration is known as the complete oxidation within a waste stream of combustible materials and operates as temperatures above 850 °C. All feedstocks of waste addressed in this paper can be incinerated. This is one of the key advantages of incineration, the ability to deal with a diversity of wastes. Gasification in many sectors has been operating worldwide on a large basis for more than 80 years. During high temperatures (500 – 1800 °C), partial oxidation is accomplished by reducing the access to oxygen. The gases produced known as 'syngas' do not burn but can be gathered and processed for subsequent use. Pyrolysis operates similarly to gasification where partial oxidation is used to maintain thermal conditions. While this development is not new, a widespread deployment has not yet been accomplished. The process operates at about 300-700 °C. Anaerobic Digestion (AD) is an established process for the treatment of organic waste within the waste to energy sector. In 2007 the Department for Environment, Food and Rural Affairs recommended companies in England and Wales to use AD to better achieve electricity goals. Interest decreased because of concerns about economic viability. AD is still considered a key process for achieving a circular economy, increasing resource-efficiency and for the bioenergy-economy. Hydrothermal liquefaction is the thermochemical conversion of biomass into biocrude oil that can then be refined into petroleum derived fuels. The process is conducted in a 4 to 22 MPa pressurised environment at temperatures 250-374 °C. With promising biomass yields this process can become more widespread in the future in the waste-to-energy sector.

The rise in WtE has contributed to energy recovery increases in the UK with tonnage of processed wastes up to 7.3 million in 2018, nearly 4 times that of 2014 at 1.9 million [1]. The estimated range of total biological waste in the UK in 2020, including forestry residue and sewage sludge waste streams, amounts to 406.86 PJ, as shown in Table 1.

Table 1. Summary of UK maximum estimates of potential for biological waste streams

Waste stream	Petajoule [PJ]	Reference

Renewable fraction of waste	43.7	[3]
Straw	132	[4]
	88.5	[5]
Food waste	46.9	[3]
	38	[4]
Green waste	10	[4]
Livestock manure	16.4	[3]
Sewage sludge	12.4	[3]
Used cooking oil	9.66	[4]
Forestry residues	8.3	[3]
	19.2	[6]
Arboricultural arisings	46	[3]
Landscape care wood	35.8	[6]
Total	406.86	

*1 Mtoe = 41.868 PJ

Large amounts of waste are now processed at facilities capable of energy production. On top of this, wastes once discarded into landfills through enhanced landfill mining, can be dealt with past and present, altering previous perceptions of what a landfill is, considering them simply as ''temporary storage awaiting further processing'' [7], with vast amounts of valuable materials and heavy metals that can be recovered. The waste generated worldwide is losing its potential contribution to sustainable living. Therefore, this paper looks to review the different wastes and the processes involved in WtE and assessing process capabilities and waste streams that can be incorporated. It also looks at the question on what more can be done and what if any significant waste streams remained untapped or not utilized to their full potential, how this can cause significant environmental and sustainable problems.

This paper also emphasizes on manure that has great potential to be used as energy source in anaerobic digesters if implemented on small scales at local farms. A global concern is poor production and utilisation of nitrogen (N), phosphorus (P), and potassium (K) from livestock [8]. Organic matter and nutrients recycled in manure are essential for agricultural soil structure and nutrient content [9]. Manure has a natural nitrogen and phosphorus content so if it is not utilised as a fertiliser on agriculture, natural nutrient cycles are disrupted, possibly that nutrient leaching, so artificial fertiliser needs are generated. Nitrogen fertiliser processing requires extensive usage of natural gas and produces pollution that lead to global warming [10]. In addition, it is stated that existing usage of small phosphate supplies for phosphorus fertiliser is unsustainable [11]. Therefore, some issues may be mitigated by rising the use of artificial fertiliser by reusing manure.

On the other hand, the vast quantities of excreta produced in localised areas will add to the nutrient excess at the regional level [12]. Excessive use of manure as an organic fertiliser can contribute to soil and water eutrophication, pathogen transmission, air contamination, and greenhouse gas emissions [13]. Sustainable processing of these large units of output is only possible if manure is reused properly. Composting is a potential stabilising procedure. A significant drawback, though, is the strong nitrogen depletion. This phenomenon decreases the fertiliser benefit and may cause odour disturbance and present a serious environmental threat [14]. An option to eco-friendly treatment is anaerobic digestion (AD), which provides added advantage to restore the caloric content by biogas production. Unfortunately, manure 's strong nitrogen content is prohibitive to successful AD. Organic Nitrogen is transformed to ammonia through microbial degradation. Ammonia exerts a strong inhibitory influence on microbiological conversion at high concentrations. Non-dissociated free ammonia triggers the toxicity [15, 16]. This compound diffuses into cells, causing a proton imbalance or interfering with microorganisms' metabolic enzymes [17]. Overcoming ammonia inhibition is essential to effective manure AD.

To make this implementation feasible and sustainable, we have highlighted the need for further processing and changing application methods of slurry and muck to land as a requirement to reduce

ammonia, methane and NOx emissions. The paper also discusses the barriers in the form of inadequate high banding tariff and systems, planning, high capital costs, lack of government subsidies and low biogas yields. It has been suggested that a lower high-paying tariff banding system needs to be introduced to increase anaerobic digestion plants on farms. It is required addition of a gate fee payment to reduce the high energy crops use as supplements for biogas yield, and to increase the amount of slurry and muck that are digested. The paper also discusses the bespoke nature of anaerobic digesters on farms and the scales of anaerobic digestion plants. The value of this paper is that it has reviewed different challenges and aspects of implementation of anaerobic digestion systems on farms within a framework of waste-to-energy conversion.

In addition to technological and environmental prospects of WtE, previous studies also tried to understand social acceptance of wate to energy and renewable energy technology. Shackley et al. [18] performed work on carbon dioxide absorption and storage in Europe and found that most of the respondents accepted this issue under the regional CO_2 mitigation plan. Wolsink [19] points out that including local citizens in the policymaking phase would help strengthen the policies on social acceptance and that without societal recognition it is difficult to accomplish both waste-to - energy and sustainability targets. Social tolerance also has to be taken into consideration through decision formation. The three reasons for popular resistance to renewable energy technology were stated by Rogers et al. [20]: inadequate growth size, unreasonable cost-to-public benefit ratio and the lack of proper connexion between the local people and their views. Wang et al [21] analysed the waste management engagement in China, as well as how waste processing, sorting, collection, cost, age and education impact waste sorting satisfaction. They also examined the impact of satisfaction on participation in terms of enthusiasm, social contact and active involvement between region and gender by using systemic equation analysis from multiple communities.

Therefore, the aim of this review is to cover the current status of WtE, understand its limitations, advantages, environmental effects, identify challenges in regards to the implementation of the waste, and assess what can be done to further utilize waste to energy in the effort to reduce pollution, resolve waste disposal issues and address energy needs.

2. Sources of waste feedstock

There is a significant discussion on the sustainability of bioenergy in Europe and the United Kingdom in particular, sparked by the recognition that increasing bioenergy use has larger environmental and social effects than was previously expected. The effect of expanded crop production for bioenergy usage on land use and the implications for the bioenergy profile of greenhouse gas (GHG) are significant environmental concerns. Increasing global demand for main grains and other crops for bioenergy processing results in increased competition on global agriculture markets, which decreases food prices to differing degrees [22]. This coupled with land purchases from primarily subsistence farmers for the development of large-scale bioenergy crops is the primary source of worry over the social impacts of traditional bioenergy.

The bioenergy produced from waste and residues is considered a way to boost environmental and social efficiency and industry credibility and to save more GHGs than conventional energy. Nonetheless, there are concerns about the viability of other feedstocks and the amounts of biomass accessible to the bioenergy industry as a feedstock. Considering that the UK energy market must be decarbonized, it is important to consider 1) possible domestic waste and residue that can help minimise the effect of UK biofuel use on biologically, socially and economically, including the ILUC impacts from outside the UK; 2) sustainable waste and residue amounts that could be required in advanced processing of biofuel; 3) the growth of job opportunities in the United Kingdom as a consequence of setting up a bioenergy industry in sustainable development.

2.1 Biomass waste

The efficient use of biomass waste offers an extensive range of advantages. Apart from fulfilling the requirements of public services, biomass can be a tap alternative sources of carbon and play a key role in a production energy system using renewable sources without decreasing food and feed stocks.

There exists a great variety of biomass waste that can be used for bioenergy production. One common type is straw, which is a by-product of the cereals harvest, but the definition may be further specified to include oil-seed rape grain and maize-growing 'substantive.' There are a variety of common applications both in the farming industry and beyond. The large-scale usage as field improvement, livestock bedding and the substitute for fodder are significant applications in the UK. Straw is also used for mushroom and horticultural production. Apart from growing, straw is used as stalk and more commonly as a building medium and for direct combustion for heat and electricity production.

As a bioenergy feedstock, the sustainability of straw is highly linked to its scale, its location and removal from current applications which can benefit from their own impact. Kretschmer et al [22] address the potential for European straw usage as well as the adverse effects of excessive straw diversion on energy usage, including: the degraded capacity of the soil, particularly through a reduction of organic soil content and consequently of nutrients; potential long lasting impacts on fauna arising from shifts in stubble heights and straw control and impact on livestock health because there is no readily accessible option to roughage and bedding (like sawdust or wood chipping). For 2020, multiple reports forecast the availability and order of straw for different purposes. As Table 1 shows, the results vary greatly. One potential explanation is the challenge of taking into account regional differences. Depending on these reports, the amount of 18 to 132 PJ of straw for UK bioenergy output was predicted for 2020 by Smith [4]. The UK's straw capacity is 88.5 PJ from a European report that offers forecasts for different countries [5].

Another type of biomass waste is woody residues. Smith [4] stated that most of the UK 's new forestry (roundwoods and residues) products were recycled into the sawmill industry and the panelboard industry. Given the high proportions of (mostly private) under management forests in the UK, however, the supply of residues is likely to increase significantly, with certain materials available for the energy sector as a feedstock. It may have positive side consequences, such as providing local work, which also contribute to habitat upgrades. Increasing the production of forestry residues by better management was one of the specified goals of the new forestry policies and strategies of the UK, in particular the Woodfuel Strategy and the Woodfuel Implementation Plan 2011-2014 of the Forestry Commission. It is expected to produce another two million renewable tonnes (residue and plant) of wood biomass each year by 2020 by: 1) Setting requirements for a profitable and safe wood fuel supply chain; 2) Capacity building by market growth and reduction of obstacles to forest management; 3) Ensure that, in close collaboration with the Biomass Energy Center (BEC), access to specialist expertise leads to business growth.

2.1. Landfill mining

This feedstock is the result of landfills ‘reopening’ to be extracted of their sources of valuable and combustible material wastes. As landfills are known to incorporate a large degree of different wastes, the exact chemical constitution can vary considerably. Prior to the European directive in 2001, there was little control in the way of what ended up in landfill sites, giving rise to concerns of hazardous wastes and indeed the effects to the environment [23]. That said typically plastics, organic wastes, different kinds of metals, textiles, wood and rubber are most commonly found in the feedstock based on the combinations of waste ending up at landfill. Table 2 gives a brief outline of these sources. These main raw materials may be mixed in with contaminates containing elements such as sulphur, chlorine and heavy metals. Bosmans et al. [7] showed that the presence of these elements can greatly affect the quality of the products produced though waste valorisation such as the syngas, bottom ash, fly ash, digestate and vitrified slag. Increasing the need of specialized abatement technologies required to reduce the amount of pollutants in the products or emissions to the atmosphere. These technologies take the form of flue gas cleaning systems.

Table 2. Different landfill waste streams

Source	Types of different waste streams

Commercial and Industrial waste (CaIW)	Paper, packaging, metals, tyres, textiles and biomass [24]
Municipal Solid Waste (MSW) (Household waste)	Paper, cardboard, metals, textiles, organics
Refuse Derived Fuel (RDF) (processed CaIW and MSW)	Separation of recyclables, non-combustibles from source. Shredding/size reduction may include pelletizing. Processing done to adhere to a fuel specification.
Solid Recovered Fuel (SRF)	Similar to RDF but less contaminated and more homogenous, adheres to more stringent specifications [25]
Scrap Yard Shredder Residue (SYSR)	High degree of plastic and mixtures, metals, rubber glass, wood, leather, textile, dirt and grit. Mainly result of automotive scrappage [26]

Note that the streams shown in Table 2 are in their own right different wastes that can be utilized for energy or product extraction if landfill is circumvented all together. Where Table 3 provides the typical properties that can be expected from MSW and RDF.

Table 3. Characteristics of MSW and RDF

Source	% C	% H	% N	% O	% VM	Lower heating value (MJ/Kg)	% water	Ref
MSW	49.5	5.60	1.33	32.4	87.1	18.7	34.2	[7]
	35.8	4.8	0.78	24.3	67	15.2	32.4	[27]
	43.71	7.73	1.95	37.66	77.66	18.5	20	[28]
RDF	54.6	8.37	0.91	34.4	88.5	22.6	10.8	[7]
	48.2	6.4	1.22	28.4	75.9	17.8	20	[29]
	48.5	6.4	1.2	31.3	83.5	20.9	26.51	[30]
RDF (From landfill)	54.9	7.38	2.03	NA	80.4	22	14.4	[7]

2.2. Food waste

The definition of food waste is taken from Lebersorger and Scheinder [31] where it includes solid components from food preparation residues, post-preparation and consumption residues, part consumed food and whole unused food. The main sectors according to Skaggs et al. [32] from which this waste arises are firstly industrial food processing centres; secondly, institutions such as hospitals, universities, schools, prisons; thirdly, commercial enterprises such as restaurants, grocery stores, food distribution centres; and fourthly residential units. A degree of this waste is averted through a food waste recovery hierarchy before the level of energy and product extraction. This type of waste is known to be of high value in its uncontaminated state where a large part at the industrial level waste can be used to create animal feeds. The types different from the animal feeds are opened up to energy and combustible product extraction and through anaerobic digestion. Looking at published work, generally speaking, the degree to which the feedstock is valued revolves around the moisture content [33,34,35]. Where a lower moisture content increases the combustion characteristics and suitability to associated processes, also reduces energy loss through steam/drying. A higher moisture content increases suitability for digestion. Table 4 shows typical composition of food waste in UK.

Table 4. Characteristics of typical food waste

Source	% C*	% H*	% N*	% O*	% VM* Of TM	Higher heating value (HHV) (MJ/Kg)	% Lipid	% Protein	% Carb	Ref
UK	52	6.9	3.1	38	22	22	15	21	48	[36]
Korea	51.2	7.2	2.9	38.1	-	-	-	-	-	[37]
Various	-	-	-	-	-	-	6.4-24.1	3.9-21.8	24-46.1	[38]
Malaysia	47.4	6.9	3.3	38.7	-	17.45	-	-	-	[39]

2.3. Fats, Oils and Grease (FOG)

Large institutional kitchens, restaurants, cafeterias are responsible for the production of waste/used oils, fats from animals and grease through cooking. A percentage of this waste inevitably ends up down sinks and in the sewers whereas they are non-water soluble can collect and form blockages. The Environmental Protection Agency (EPA) has estimated FOG build ups contribute to 70% of sewer pipe blockages and 30% of pump station failures [40]. Water UK [41] provides guidance on avoiding fats and oils from entering the sewers for large kitchens where grease traps are the primary means of capture. This works via taking advantage of the difference in density of water and FOG to capture and contain the grease to be disposed. This grease can contain a wide range of suspended waste food solids and wastewater, and as such, is known as 'brown grease'. These contaminates make it more difficult to recycle than 'yellow grease' which is from spent oils and fats that have not interacted with wastewater i.e. deep fat frying. Due to this contamination, the brown grease is not used for biodiesel production due to lower energy content of 35 MJ/kg compared to 40 MJ/kg of waste cooking oil. [42]. So, the brown grease is usually disposed as waste rather than recycled into energy. There are many options in regards to utilizing yellow grease in anaerobic digestion, composting, processing into biodiesel as mentioned, or used as additives for animal feed and soap. But the uses of brown grease are not so clear with its hazardous classification and more difficult extraction procedures.

Other than waste oils, fats and grease from the cooking industry, a large amount of synthetic and mineral oil wastes accumulate when they are no longer deemed fit for purpose. These are motor oils, heating oils, hydraulic oils, ship oils, sump residue and oil-water emulsions. All categorized as hazardous waste due to the chemical makeups used. For example, used engine oil contains cocktail of hydrocarbons, heavy metals (magnesium, cobalt, zinc, iron), minerals, chlorine, sulphur, phosphorus, nitrogen and additives all known to have cancerous effects and detrimental to the environment [43]. The environment protection agency states that one drop of used motor oil can contaminate 1 cm^3 of water, highlighting the scale of potential cause when considering if all vehicles that have internal combustion engines produce waste oils.

2.4. Wastewater sludge (WWS)

During the processing and treatment of wastewater to return it to the environment, a residual nutrient rich semi-solid is produced known as wastewater sludge (WWS), typically containing 25-75% solid based on weight. WWS can be composed of solids from primary and secondary treatment stages. During the primary stage, the initial suspended solids within the wastewater are separated. Around 40-70% of solids within the wastewater are captured, where the organic and inorganic fines are concentrated down to 2-7% and 60-85% for volatile suspended solids. Secondary treatment stage focusses on biological aspects where a combination of aeration, exposure, microbes and secondary settling occurs. Solids are concentrated to 0.5-1.5% with volatile suspended solids concentrations at 70-80% [32]. Biochemical characteristics of primary and secondary sludge are shown in Table 5.

In the US approximately 6.3 million metric tons of municipal WWS was produced in 1998 of dry solid weight (according to the US environment protection agency) and todays figure will only be higher. When processed properly it can be very beneficial for the application of agricultural land to improve soil quality, using as a soil conditioner in landscaping, and using for part of landfill cover-ups [44]. Hence the term 'biosolids' is associated with processed WWS. The main energy recovery process associated with WWS is anaerobic digestion, in which the resultant bio-waste and indeed the treated WWS can be used in the production of biosolids for fertilizer. However, there are social concerns in regards to heavy metals and pharmaceutical compounds that could be within the WSS. Which, when introduced to agricultural cropping soils can give a predominately negative effect on local water, energy and material sustainability [45]. In addition to affecting the ecosystem through concentration of heavy metals, crucially highlighting contaminates play negative role in reducing the sustainability and product quality. An option that reroutes the biosolids from being used as fertilizers and averting the social concerns is hydrothermal liquefaction processing into bio crude oil. This bio crude oil can then be refined to meet bio diesel and diesel standards [46].

Table 5. Biochemical characteristics of primary and secondary sludge

Source	% C	% H	% N	% O	% VM	HHV (MJ/Kg)	% Lipid	% Protein	% Carb	Ref
Primary sludge	47.8	6.5	3.64	33.6	82.17	20.7	-	-	-	[47]
	51.5	7.0	4.5	35.5	65	-	18	24	16	[48]
Secondary sludge	43.6	6.55	7.9	29.0	76.25	19.6	-	-	-	[47]
	52.5	6.0	7.5	33.0	67	-	8	36	17	[48]

2.5. Manure

This is the combination of animal faeces with an agricultural by product such as straw (used as animal bedding). All livestock, particularly indoor bred stock produce manure. This manure can vary in composition depending on the type of animal it is from and what diet they are on. Table 6 shows these differences in the biochemical characteristics.

Table 6. Characteristics of different manures at 76.37% water content

Source	% C	% H	% N	% O	% VM	HHV (MJ/Kg)	% Lipid	% Protein	% Carb	Ref
Fattened cattle	35.38	3.73	2.38	57.51	16.21	15.16	6.8	26.6	52.5	[32]
Dairy cows	38.8	5.1	1.3	54.7	83.2	11.9	5	18.11	52.6	[32]
Bacon pigs	41.1	5.42	3.36	50.1	83.7	-	20.3	24.5	34.7	[32]

Fertilization is the primary use for this type of fully biodegradable waste where without any processing it is spread onto crop producing land. A common life cycle is known to be set up between arable and livestock farmers in the UK as a result where manure is exchanged for straw. Where the manure is desirable for arable farmers to fertilize their land and the straw from the crops produced by the arable can provide a bedding and food source for a livestock farmer [49]. This is the virtually at present the only pathway for disposing the manure and slurry. Processes such as anaerobic digestion (discussed in the next section) aim to tap into the vast amount of energy stored within this feed though emitted products. Nitrous oxides, methane and ammonia are the most prevalent gasses released into the atmosphere by the decomposing manure without any process intervention. This is of great concern given the amount of manure produced every year and known the global warming characteristics of said gasses. The animal agriculture sector accounts for 37% and 64% of the annual anthropogenic methane and nitrogen oxides emissions, respectively, which are 23 and 296 times the global warming potential (GWP) of carbon dioxide. In addition, livestock are responsible for 64% of the anthropogenic ammonia emissions, contributing to the formation of acid rain and acidification of ecosystems [50]. Such high percentages are alarming considering that the majority of these emissions are from manure and slurry and highlight the need for processing to bring emissions in the sector to some acceptable level.

3. Waste-to-Energy Processes

Waste-to-energy encompasses a variety of specific methods and technologies. In the purposes of this article, this is intended to identify a variety of disposal methods and techniques utilised to produce a functional source of energy and to minimise the amount of residual waste. Such energy may be in the form of power, heating and/or cooling, or turning the waste into a product for potential usage, such as biogas, automotive fuels, or a mixture of these types. In this paper we will review the conversion of waste to energy through the following processes: incineration, gasification, pyrolysis, anaerobic digestion, and hydrothermal liquefaction.

3.1. Incineration

Incineration is classified as the full oxidation of the combustible materials within a waste stream. The process is composed of several key stages of drying/degassing, pyrolysis and gasification then combustion. Unlike other processes in this list that only partially oxidize the waste stream, incineration can be fed by a large variety of waste streams. In fact, all waste streams discussed in this paper can be incinerated. This is one of the main advantages incineration has, the ability to deal with a high degree of waste variety. The variety effects the product percentages left after processing, such as the bottom ash which in MSW incinerators is approximately 25-30 % by weigh of dry waste input, and the fly ash is at 1-5 %. The fly ash requires immobilization to be made environmentally safe, which can then be used in asphalt concrete. The bottom ash however requires much more processing, where at a slag reprocessing pilot plant facility, valuable metals (Al, Fe, Cu) can be recovered. The residue after metal recovery can then be granulated for the construction industry [51]. Figure 2 is an example diagram of a combined heat and power (CHP) plant based on incineration.

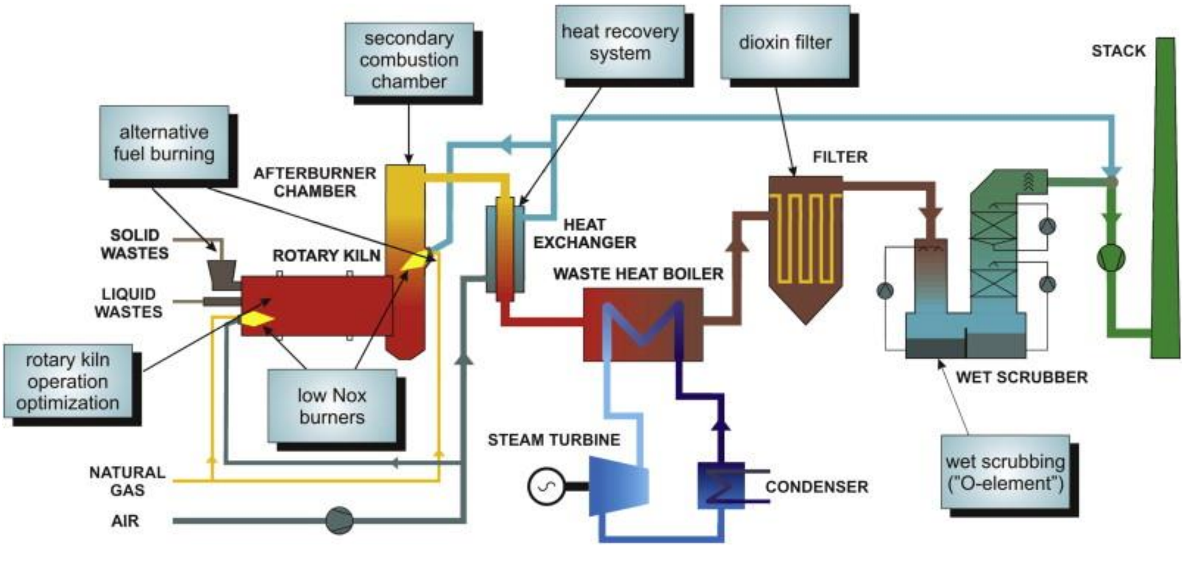


Figure 2. Simplified layout of a waste-to-energy incinerator [51]

Originally, incineration was purely used to reduce the volume of waste as well as destroy harmful substances in the effort to prevent health threats. Now, waste incineration is predominantly combined with energy recovery the importance of which is increasing. Denmark and Sweden are notably the world leaders having produced electricity from the incineration of waste for more than 100 years [52]. Now there are 3 main types of incinerators; gate, rotary kilns and fluidized beds, each type specified for particular feedstock. The plant efficiency factor of these incinerators according to the confederation of European WtE plants (CEWEP) in 2010 based on accounted 314 plants was at average 0.69. The specific electricity produced as weighted average was 14.89% of total Mg and heat at 34.59% of total Mg [53]. Note that the Plant Efficiency Factor ($R1$) in the equation (1) was used to obtain the figures given in accordance with the waste frame directive [54]. WtE plants "producing electricity only" have the lowest $R1$ factor of 0.55, as a non-weighted average, so that only 37.3% plants reach $R1 \geq 0.60$. Although WtE plants "producing heat only" have a higher $R1$ factor of 0.64, as a non-weighted average, only 68.1% plants reach R1 ≥ 0.60. In this case, the import of the total amount of electricity to treat the waste has a negative influence. WtE plants "CHP producing" achieve the highest $R1$ factor of 0.76, as a non-weighted average, so that 77.2% plants reach $R1 \geq 0.60$.

$$R1 = \frac{(E_p - (E_f + E_i)}{\left(0.97 \cdot \left(E_w + E_f\right)\right)} \tag{1}$$

where, $R1$ - plant efficiency factor, E_p - annual energy produced as heat or electricity, E_w - annual energy contained in the treated waste, E_i - annual energy imported, and E_f - annual energy input to the system from fuels contributing to the production of steam [53]. These plants are notably still less efficient than conventional power plants. This is in part due to specific equipment requirements for incineration of waste, limitations on steam pressures due to corrosion risks, energy requirements to maintain optimal operational regime and critically pollution control equipment necessary to treat flue gasses. Generally, the more effective and complex a pollution control system is the higher the energy needs.

The current status of this technology in the UK is at TRL 9 since the actual system is proven in an operational environment. In 2016 there were 115 incineration facilities in the UK. It is estimated that 6.1% of waste generated in the UK is processed through incineration [55, 56]. 37 incineration facilities were fitted for energy recovery accounting for 3.4% of waste processing, as shown in Table 7. This equates to 7.3 million tonnes of waste. It is in increase from 2014 where only 0.9% of waste were processed with energy recovery representing 1.9 million tonnes of waste. Three new facilities were commissioned between 2014 and 2016, however, the total number of incineration facilities with energy recovery increased by eight. It is likely that new facilities are designed for energy recovery, while older facilities without energy recovery are converting to enable energy recovery. It is foreseeable that the number of incineration facilities with energy recovery will increase over the next decade as older facilities are converted.

Table 7. Use and capacity of incineration facilities in the United Kingdom [55, 56]

Incineration in the United Kingdom								
	Incineration only				Incineration with energy recovery			
Year	Mt	Capacity Mt/yr	% of all waste	Number of facilities	Mt	Capacity Mt/yr	% of all waste	Number of facilities
2012	5.9	8.4	3.1%	87	1.6	2.9	0.8%	27
2014	7.6	9.9	3.7%	83	1.9	4.9	0.9%	29
2016	5.7	8.5	2.7%	78	7.3	9.8	3.4%	37

The UK Strategy for Recourses and Waste reported that 3.4% renewable energy was generated from incineration of biodegradable waste in 2017 [57]. It is estimated that 2.3% of the UK's energy demand can be met through incineration with energy recovery should all the municipal solid waste that are currently sent to landfills be rerouted to incineration facilities [58]. Not only will this have a positive effect on the renewable energy generation in the UK, but also on greenhouse gas emissions generated from landfills. It is plausible that greenhouse gas emissions can be reduced by 2 million tonnes in this manner [106]. Legislation requires that biodegradable waste sent to landfills must be significantly reduced. This will see more municipal solid waste rerouted to incinerators providing an increase in feedstock and more opportunity for energy recovery from incineration. However, the current stance of the UK Government is that although incineration plays an important role in waste management the focus should be on prevention and recycling rather than landfills and incinerators. Taxation on the incineration of waste is likely to increase over the next few years which may reduce the economic benefit of this manner of waste management.

3.2. Gasification

Gasification has been around for some time more than 80 years globally on a commercial scale in many industries and 35 years in the power generation. In partial oxidation process of organic substances, high temperatures of around 500-1800 ℃ are used. Partial oxidation is achieved by limiting the oxygen exposure at those temperatures so the gases produced known as 'syngas' do not combust but instead can be collected and stored for later use. These later uses include the chemical industry, as a fuel for the production of heat and or electricity or conversion into ethanol [59]. The syngas constitutes of H_2, CH_4, CO, CO_2, H_2O and N_2 with trace amounts of other hydrocarbons like propane and ethane. Predominantly air is supplied to the reaction site which in comparison to using pure oxygen results in a syngas of lower energy. Such that, in terms of heating value, pure oxygen gives 8.7 - 11.3 MJ/Nm^3 and air gives 4–7 MJ/Nm^3 [60]. There are 3 main types of gasifiers: fluidized bed, fixed bed and entrained flow which are capable of dealing with MSW, dried sewage sludge, some types of hazardous wastes and waste food among others. One of the key requirements for the feedstock is that it must be finely granulated, therefore MSW for instance requires pre-treatment. This is a clear negative side when compared to incineration, which comparatively has lower residue percentage of the feedstock. But there are positive comparisons such as lower volumes of gases produced mean smaller flue gas treatment systems can be used and smaller wastewater flows from syngas cleaning [7]. In addition, the overall thermal efficiency is more than 75% [61]. Furthermore, by the use of partial oxidisation, the amount of oxidized species such as SOx and NOx are reduced, which are replaced by H_2S, nitrogen and ammonia. Known to be better forms that can be scrubbed from the syngas than the oxidized versions prior to syngas utilization [62].

In terms of gasification process a number of sub process take place. These constitute of a degree of pre-processing to remove inorganics such as metals and glass, which cannot be gasified, particle size reduction, drying (within the gasifier and in some cases prior to), oxidation and syngas collection. As can be seen the main waste product left over is slag (in high temperature gasifiers), this is similar to the bottom ash in the incineration process where metals and other valuable products can be recovered. Gasification of fossil feedstocks is an established process and is therefore rated at TRL 9. The use of biomass feedstock, such as municipal solid waste, is not readily applied in the UK. Although there are a number of plant in Norway, Germany, Finland, Italy and Sweden [63]. It was recently reported that operation had begun at UK's first municipal solid waste gasification plant located in Aldridge [64, 65]. To date the plant is operating on waste wood feedstock and the technology is not proven for municipal solid waste, although it is the intension to do so in the future. This is not the first gasification plant constructed in the UK for processing of biomass waste. Several such facilities have been built in the past and all have failed [66, 67]. One such example is the company Energos Ltd. that operated a gasification plant in the Isle of Wight since 2009 [68]. The plant made use of Refuse Derived Fuel (RDF) and was designed to provide 1.8 MWe power. The company had plans to build similar plants in Glasgow, Milton Keynes and Derby. However, the plant went into administration in 2016; the route cause was found to be a failure to deliver on gasification contracts. Another example is Ascot Environmental and its subsidiaries Planet Advantage and Scotgen that build a gasification plant in Dumfries in 2009. The plant was designed to deliver 6.2 MWe power from municipal solid waste and RDF feedstock. The company filed for administration in 2012 since the plant failed to produce energy during its three years of operation. The permit to operate that plant was revoked due to non-compliancy with the Scottish Environmental Protection Agency.

Fiscal incentives for the development of advanced conversion technologies, such a gasification of municipal waste, might receive more attention in the next decade [69]. The Engineering and Physical Sciences Research Council (EPSRC) does not have a specific research focus in this area but has supported gasification projects in the past [70]. Considering the past failures of the technology, it will be challenging to obtain the necessary funding to increase the TRL. Much depends on the operation and economic viability of the Aldridge plant and its ability to robustly process municipal solid waste on a large scale. The success of this plant will unlock the potential for gasification as biowaste processor. The failure however, along with the historical failure of similar plants, will be seen as conclusive proof that further development of this technology should be abandoned.

3.3. Pyrolysis

This process works on the thermal degradation similarly to gasification where partial oxidation is used to maintain the thermal conditions. Pyrolysis can also be achieved in complete absence of oxygen with an external heat source in inert conditions. Comparatively to gasification, pyrolysis works on lower temperatures of around 300 - 700 ℃ [71]. To date, although this technology is not new, it has not yet reached a widespread implementation. During the process, 3 products are made: solid coke, pyrolysis gas, pyrolysis liquid. The exact constitution and proportions of these products depends on the feedstock, reactor conditions, reactant residence time and pyrolysis method. The process can be optimized to maximize the formation of each product [72]. For example, in the case of fluidized bed reactors (fast pyrolysis), high temperature and high biomass residence time increases the production of gases; On the contrary, high temperature and low residence time however increases the formation of condensable liquid oils; then low temperature and high residence increases the production of solid coke. Typically, the pyrolysis gas, liquid and coke have calorific values of 5-16 MJ/kg, 22-25 MJ/kg and 33 MJ/kg respectively. The low heating values of the gases and liquids mean that upgrading is necessary to produce fossil fuel substitutes [73]. Pyrolysis can work on any hydrocarbon waste that can be cracked to release gasses, oils and char. For instance, FOG, MSW, food waste, manure and sewage sludge are all acceptable.

One of the notable advantages of pyrolysis against other waste-to-energy processes is the higher energy density achievable of the products produced. But what some researchers don’t mention is that these higher energy products were produced with external heat sources supplied to the reactor. Furthermore, a degree of preparation is required to reduce feedstock particle size. Also, drying can be required depending on moisture content and the desired calorific value of the products. The inner stages are centralized around the reactions (thermal cracking) of the waste to release the pyrolysis products, which are then captured through condensing. The remaining coke is sometimes incinerated to rid of the organic matter remaining. Main pyrolysis reactor types include rotary kiln, fluidized bed, fixed bed, entrance flow, moving bed and more experimentally auger [74]. As hinted here, this process can be responsible of higher waste residue than gasification and incineration. This is mainly due to lower temperatures as a result of lower flue gas volumes after combustion of the products than incinerators [7].

As a general process, fast pyrolysis is currently deployed in operational environments with system completion and qualification. This places fast pyrolysis at TRL 8. Pyrolysis with upgrading, that increase the quality for the oil produced so that it can be used as transport fuel, is currently at TRL 5 [70]. There are 8 companies and 9 universities actively engaged in activities related to waste treatment through pyrolysis (Table 8). Activities are mostly aimed at waste-to-fuel applications instead of waste-to-energy. There are currently no large-scale facilities for pyrolysis in the UK.

Table 8. UK Companies and institutions involvement in pyrolysis

Company/Institution	Location	Feedstock	Conversion	Ref
2G BioPOWER	Kent	Tyre	Recycling	[75]
Anergy Ltd	London	Biomass	Waste-to-Energy	[76]
Conversion and Resource Evaluation (CARE) Ltd	Down	Biomass	Waste-to-Fuel	[75]
Cynar Plc	London	Plastic	Waste-to-Fuel	[76]
Environmental Power International	Surrey	Various	Waste-to-Fuel	[76]
Future Blends Ltd	Oxfordshire	Biomass	Waste-to-Fuel	[75]
PYREG (UK)	Cambridge	Sewage Sludge	Phosphorous Recovery	[75]
Torftech Energy Ltd	Thatcham	Biomass	Waste-to-Energy Waste-to-Fuel	[75]
Aberystwyth University	Aberystwyth	Biomass	Waste-to-Fuel	[75]
Aston University	Birmingham	Biomass	Waste-to-Fuel	[77, 78]
Newcastle University	Newcastle	Biomass	Waste-to-Fuel	[75, 79]
University College London	London	Plastic	Waste-to-Fuel	[80, 81]
University of Cambridge	Cambridge	Various	Material Recovery Waste-to-Fuel	[75, 82]
University of Edinburgh	Edinburgh	Biomass	Waste-to-Fuel	[83, 84]
University of Leeds	Leeds	Biomass	Waste-to-Fuel	[85]
University of Sheffield	Sheffield	Biomass	Waste-to-Fuel	[86, 87]
University of York	York	Biomass	Waste-to-Fuel	[88]

The EPSRC are routinely funding research aimed the development of bioenergy. The bioenergy thematical area currently holds 14 research grants worth £12,511,100.00. There are a number of grants awarded that is specifically aimed at improving the pyrolysis process. These were all related to waste-to-fuel applications focusing on upgrading the quality of products to be used as marine and aviation fuel. Funding for waste-to-energy applications of pyrolysis remains uncommon. The financial and technical challenges will hamper the integration of pyrolysis as a process for waste management in the next decade. Pyrolysis as waste-to-energy mechanism is subjected to technical challenges [68]. The feedstock from municipal solid waste is inconsistent and will need significant preprocessing before it can be used. Blockages are often caused in pyrolysis plants due to tar deposition which lead to inefficiencies. Catalyst deactivation and choking can result in plant failure. These challenges are not negligible and has led to the limited application of this process worldwide.

3.4. Anaerobic digestion (AD)

As with incineration and gasification, Anaerobic Digestion (AD) is a well-established process within the waste to energy sector for the treatment of organic wastes. Dating back to the 1800s making it one of the oldest waste to energy processes. The concerns around the environment has increased its utilization when in 2007 England and Wales businesses were encouraged to use AD by the department for environment, food and rural affairs (DEFRA) to help meet energy targets set by the government [89]. Now, however, interest has dropped due to economic viability concerns. Investments and interest primarily come from businesses such as farms and not large waste industry companies, as the case studies included in the Royal Agricultural Society of England report show [90]. One of the main differences between AD and incineration/gasification is the predominantly large plant waste treatment centres, costing hundreds of millions. However even with the economic concerns, AD is still considered a key process for achieving a circular economy, increasing resource-efficiency and for the bioenergy-economy as a whole [91].

The main feedstock for AD is manure and slurry, but it is not limited to these. Essentially, any organic matter can be fed into the digester such as WWS, FOG and food waste, as the process works on decomposition of organic matter. Microorganisms digest/eat the feedstock producing biogas, predominantly made up of methane (50-75%), with carbon dioxide along with traces of other gases making up the remaining percentage [92]. After the process, a solid mass known as digestate is left, a nutrients rich product that can be used as a fertilizer. As for the gasses produced, the high percentage of methane means it can either be upgraded to pure methane (main constitute of natural gas) or be combusted in a CHP plant. As Bywater [90] states ''The ratio of heat to power varies dependent on the scale and technology, but typically 35-40% is converted to electricity, 40-45% to heat and the balance lost as inefficiencies at various stages of the process, equating to over 2 kWh electricity and 2.5 kWh heat per cubic meter, at 60% methane''. There are two types of AD's: mesophilic and thermophilic, categorized according to their operation temperatures. The most common type (mesophilic) operate at temperatures between 20-45 °C. Thermophilic digester operates at higher temperatures and most commonly used for sanitizing materials, so that they can be used for the benefit of agriculture.

Anaerobic digestors are widely used in the UK placing the technology at TRL 9. There are currently 661 digestors operational in the UK [93]. It supplies the national grid with biomethane (102 plants) and electricity (583 plants) and provide local heating (42 plants). The feedstock varies from agricultural waste (374 digestors), municipal/commercial waste (113 digestors), industrial waste (48 digestors), and sewage sludge (163 digestors). Between 2008 and 2017, 255 new anaerobic digestors were built in the UK with a total capacity of 193,354 kW [92].

The percentage of energy generated in the UK from bioenergy is steadily increasing (Table 9). In 2010 3.5% of energy generated were from biological sources. This has increased to 9.4% in 2016. Anaerobic digestors forms a component of bioenergy and is increasing as well. In 2010, 117 GWh electricity was generated with AD, accounting for 1% of energy generated with bioenergy. This increased to 2052 GWh in 2016, which is 7% of energy generated with bioenergy. AD is further discussed in section 4 where the environmental, economic, legislative and implementation is investigated.

Table 9. Electricity generated in the UK from bioenergy by year [94]

Source	Units	2010	2011	2012	2013	2014	2015	2016
Landfill gas	GWh	5,217	5,318	5,208	5,175	5,033	4,872	4,703
Sewage sludge digestion	GWh	723	775	739	766	840	894	950
Energy from waste	GWh	1,529	1,504	1,773	1,648	1,900	2,585	2,741
Co-firing with fossil fuels	GWh	2,432	3,093	1,829	337	124	183	117
Animal Biomass	GWh	627	615	643	628	614	648	650
Anaerobic digestion	GWh	117	237	495	713	1,023	1,471	2,052
Plant Biomass	GWh	1,615	1,771	4,048	8,832	13,086	18,587	18,829
Total electricity generated from bioenergy	GWh	12,260	13,313	14,735	18,099	22,620	29,240	30,042

Total electricity generated from all sources	GWh	347,896	332,461	341,912	336,504	317,732	318,552	320,110

3.5. Hydrothermal Liquefaction (HTL)

This is the thermochemical conversion of biomass into oils referred to as 'biocrude oil' that can then be refined into petroleum derived fuels. The main advantage of this process is that water has a higher dissociation constant (and lower dielectric constant) at these operating conditions. The water is thereby less polar and helps to be a good solvent for hydrocarbon products and promote their reactions. As shown in Figure 3, the process is performed in a pressurized environment from 4 to 22 MPa, which avoids oxygen and heats to elevated temperatures between 250 - 374 ℃ [95]. These high pressures and temperatures help breakdown and reform biomass macromolecules into biocrude oil.

As with anaerobic digestion, the process provides a means for processing wet biomass without drying that incineration, gasification and pyrolysis require. However, HTL is essentially pyrolysis in hot liquid water. As such, feedstock high in water content are suitable i.e. manure and sewage sludge. HTL biocrude oils contain a diverse range of chemical compounds, which present major challenges for downstream processes. This in some instances due to high heteroatom content in the biocrude oil can result in undesirable qualities, like acidity [96]. That said significant amounts of biocrude oil can be obtained from pig manure and digestate sludge. Vardon et al. [96] showed that at 300 ℃, 10-12 MPa and 30 min reaction time, pig manure and digestate sludge yielded 30% and 9.4% respectively with HHV's of 34.7 MJ/kg and 32 MJ/kg. With promising yields from biomasses, this process may become more widespread in the waste-to-energy sector in the future.

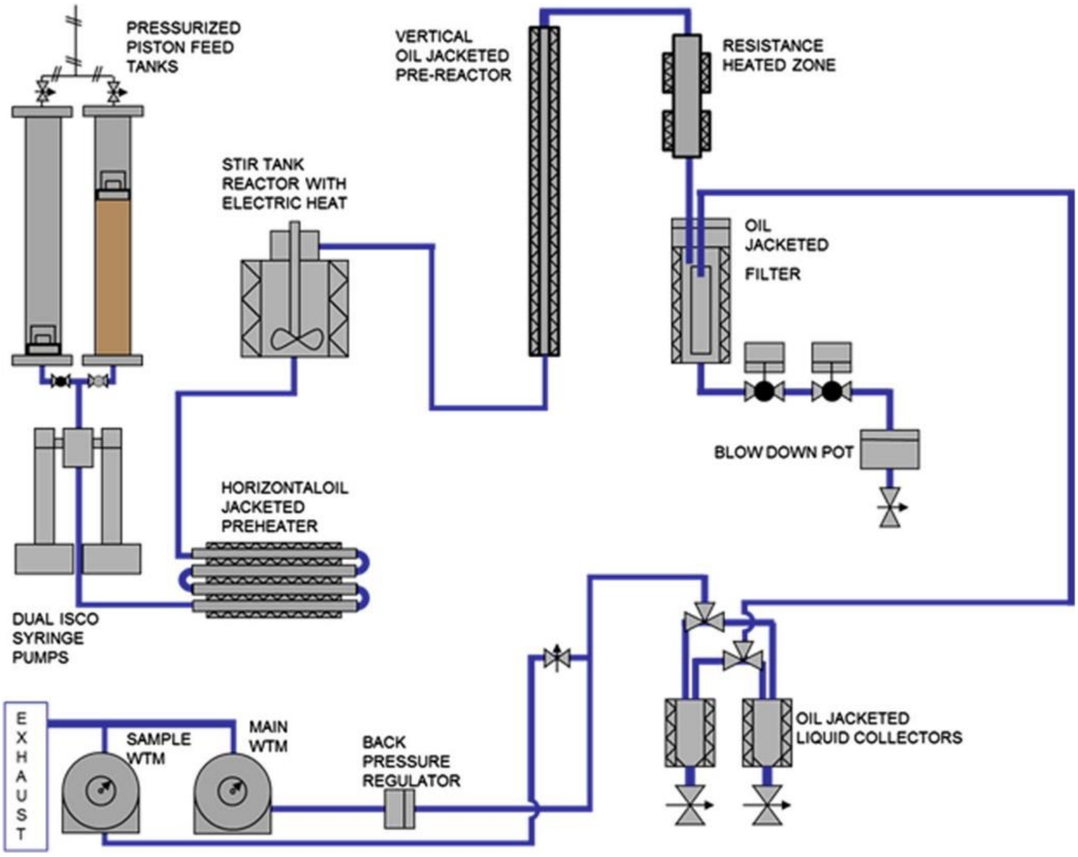


Figure 3. Diagram of HTL reactor system [95]

The current status of hydrothermal liquefaction in the UK is TRL4 since it has only been validated in the laboratory environment [70]. A recent review has indicated that the technology is immature with scaled testing at a limited number of UK universities [97]. The University of Leeds, Imperial College and Bath University are the only known institutions actively involved in experimental research in this area [98, 99, 100]. A recent review from the University of Surrey suggested the research focus for the process [101]. It highlighted the developments needed in the field to allow for both wet and dry biomass to be processed through this technique. Currently challenged associated with the process is catalyst performance, efficiency, product quality and handling of the high volumes of wastewater. Stirring large volumes of biomass slurry at high pressure is problematic and the solid content needs to be less than 35% to ensure pumpability. The process remains expensive due to the components necessary to operate in a corrosive environment at high pressures. The technology is expected to reach TRL 8 by 2030 [70].

3.6. Summary of advantages and disadvantages of WtE processes

Looking at how prolific the processes are, HTL and AD lag behind incineration, gasification and pyrolysis in the UK, aligning with some of the issues discussed. Other process, such as fermentation, is used to some extent to produce bioethanol, but this is not so prevalent in waste feedstock streams. Incineration has been shown to be the most capable in feedstock admissions combined with the lowest end process waste percentages. However, this comes at the cost of lower efficiencies, high flue gas volumes and the loss of product extraction from the waste streams. The partial oxidations adopted in gasification and pyrolysis give advantages of lower flue gas volumes of which have lower percentage levels of oxidized species such as SO_X and NO_X, resulting in smaller flue gas treatment systems.

The other main advantage is the product extraction possibilities. Notably pyrolysis process results in products of higher energy density. Although not discussed, plasma pyrolysis and plasma gasification among others are some of the technological advances of these processes, essentially working at higher temperatures to create more reactions and result in less end process. AD is shown to be different from the other processes, attaining products without the need of high temperatures and complex systems. But AD is limited to predominately manure feedstocks and economic uncertainties through lowering levels of government schemes and grants. This is alarming, considering a degree of pollution raw manure is responsible for. HTL offers a pathway to obtaining bio crude oil which can be upgraded and refined to match petroleum-based fuels from waste streams, unlike other processes that use more valuable resources, such as rapeseed biodiesel, for instance.

One thing that has been made clear across literature of WtE processes is that although some of the processes have the ability to deal with a wide variety of wastes, the facilities are usually specifically designed to suit one particular waste stream. For example, in 2009 the chimney of ConTerm pyrolysis plant in Hamm Germany collapsed. The accident was the result of an insulation problem which lead to very high temperatures and softening of the steel structure. It was later found that inadequate sorting of the waste stream was a key contributor, as the feed characteristics exceeded the process design resulting in excessive temperatures past tolerable limits [7].

The utilisation of waste streams for energy and products has proven to be well documented, with landfills now considered as temporary storage. Waste FOG’s and food can be fully utilized for WtE processes, same goes for WWS. Despite the widespread implementation/capture of these wastes in the UK, it still requires a degree of work in achieving a circular economy as the government plans.

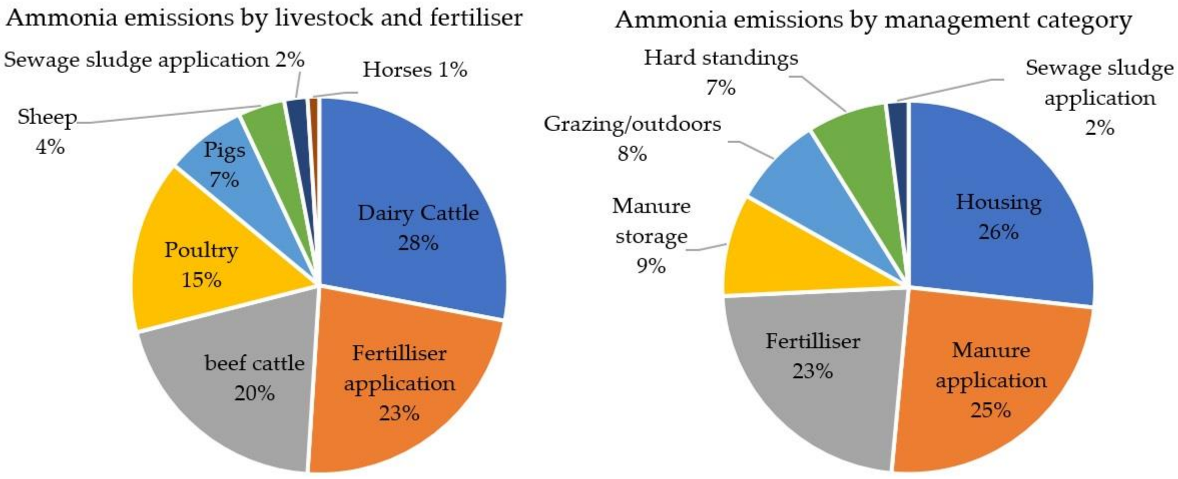
4. Discussion on the Effects of Manure and Barriers to Processing

When looking at preventative environmental emissions, manure as a feedstock remains largely untouched. As a result, high concentrations of NO_X, ammonia and methane, which are retained in the manure are emitted into the environment. A complete contrast is shown to strict legislation placed on internal combustion engines for NO_X emissions, which in fact, account for far less of the anthropogenic emissions than manure. These and other wastes discussed in the previous section should be the subject to a higher attention even if they are responsible for a lower fraction of the emissions of manure. Therefore, this section will cover the issues of manure and anaerobic digestion related to the environment, economics, legislature, and implementation. It will discuss the severity that untreated manure can pose in the UK through emissions of nitrous oxides, methane, and ammonia. Amount of emissions produced by manure can be mitigated through WtE processing by avoiding the barriers preventing the implementation of this as a whole, and also bringing most of manure generated in the UK under pollution control.

4.1. Environmental effect of emmisions from manure

4.1.1. Ammonia

Overall, the agricultural sector accounts for 88% of all NH_3 emissions in the UK and is estimated at 94% in the EU [101, 102]. The lack of manure and sludge treatment in the UK results in the livestock industry accounting for 66% of all ammonia emissions, as shown in Figure 4 (b) (not including grazing/outdoors), according to the Department for Environment Food and Rural Affairs (DEFRA) [102]. The figure related to manure and slurry production is not taking into account cattle graze on open fields for at least half a year, not counting some unavoidable proportion of ammonia (NH_3) emitted into the atmosphere. Report on NH_3 emissions produced by agriculture sector was prepared by DEFRA. Figure 4 (a) shows the proportion of ammonia emissions per livestock.



(a) (b)

Figure 4. Ammonia emissions within agriculture by (a) livestock and fertilizer category and (b) by agricultural management category [102]

An estimation from Figure 4 can be made on the true amount of NH_3 emissions, the direct result of manure formation and slurry at around 40 % (Manure storage 9% + Grazing 8% + Hard standings 7% + Sewage sludge 2%) of 66% of all ammonia emissions subject to unavoidable losses through animal grazing and hard standings. Hard standings are defined as unroofed paved or concrete areas. Examples include areas outside the milking parlor, where dairy cows congregate prior to milking. Meaning that up to 40% of NH_3 has the potential to be avoided with widespread waste to energy processes applied. This 40% in 2019 amounts to 86.2 kT of NH_3 emitted every year [103]. As NH_3 is a soluble alkaline gas with a high reactivity, the effects to the environment are numerous. In terms of the atmosphere, it reacts with acid pollutants such as the products of SO_2 and NOx emissions to produce fine ammonium NH_4+. Both forms have a lifetime of 10-100 years which lessen the overall effects atmospherically but creates localized affection zones with high concentrations of NH_3 and ammonium fallout [104]. The effects of ammonia vary as it is a commonly found naturally. One of the most notable aspects is the unpleasant odour, which even at low concentrations due to the pungency is still detectable. In the atmosphere, it can be an irritant to the eyes throat and lungs in high concentrations, the ammonium can penetrate deep into the lungs with links to respiratory problems and diseases due to the fine particle size [105].

For vegetation, ammonia is on the most part beneficial as a source of nitrogen essential for the formation of amino acids. When in the form of ammonium and is deposited onto soil it is converted by bacteria into nitrates which are then absorbed by roots increasing growing rates of nitrogen loving plants. But this can lead to imbalances affecting biodiversity, where nitrogen loving plants take over smothering out other species less effective in nitrogen take up. NH_3 pollution also effects species through soil acidification, damage to leaves through a burning effect reducing the resistance to frost, pathogens and drought. These negative effects in a report conducted by RAND [106] say that by 2020 the negative impacts could be equivalent to the cost of more than £700,000,000 per year.

The effects of NH_3 in water sources is notably more severe, with links to eutrophication and acidification, where in concentrations ranging from 0.53 to 22.8 mg/L it becomes toxic to freshwater organisms. The toxic effects differ depending on species but generally fish may suffer loss of equilibrium, hyper excitability, increased oxygen uptake and increased heartbeat rate. In extreme levels NH_3 can cause fish to suffer convulsions, coma and death. Even at levels below 0.1 mg/litre fish can experience irritation, gill damage, reduction in hatching and growth rates [107]. Fish and aquatic life can also be indirectly affected through eutrophication creating algal blooms reducing the amount dissolved oxygen.

4.1.2. Nitrous Oxides (NO_X)

This is another notable pollutant given off by manure, known for its high GWP of 298 times that of carbon dioxide. The lifetime is around 110 years in the atmosphere where the process that removes NO_X from the atmosphere contributes to depletion of the ozone layer [108]. Aside from methane and ammonia, NO_X is the 3rd biggest contributor in emissions from agriculture. The degree of NO_X produced from manure is dependent on the amount of aeration where the greater availability to oxygen leads to more NO_X formation. Looking back at the waste to energy processes, anaerobic digestion offers the most suitable option in limiting NO_X formation. The amount of NO_X emitted as the direct result of manure is unknown, however the overall NO_X emissions from agriculture are known to be 27 kT in 2017 [109]. This amounts to 3% of the total NO_X emissions in the UK, with transport contributing the most, 34%. Contradictory to this data, the national statistics for the UK in 2017 showed that in fact agriculture is responsible for 70% of NO_X emissions, amounting to 14.3 Mt CO_2e [110].. As both are from reputable governmental sources, this serves as an example of the degree of uncertainty these estimates are subject to. Nevertheless, more trust will be placed on the higher figures when looking at another report stating it to be 65% [111]. Similarly, to the NH_3 emissions, the amount emitted as the result of manure can be expected to be considerably less. 28% is a reasonable estimation if manure amounts to 40% of agriculture’s overall impact.

4.1.3. Methane

As with nitrous oxides, methane presents a significant contribution to greenhouse gases with a GWP 25 times that of CO_2 and a lifetime in the atmosphere of around 10 years, where other chemicals in the air are responsible for its removal. The main source of methane is from the natural decomposition of organic matter in anaerobic conditions. As manure and slurry present large quantities of organic matter they contribute significantly to the agricultural sectors total emissions 51% of the UK’s anthropogenic methane emissions in 2015 [112] and 50% in 2017 [110]. Figure 5 shows this in comparison to other sectors highlighting again that agriculture is the biggest contributor. Unlike NH_3 and NO_X emission where artificial fertilizer contributes heavily, methane is almost exclusively from manure, slurry and the animals’ digestive systems. As the animals are known to be high contributors a ballpark estimation would be that 45% of methane emissions within agriculture are the direct result of manure and slurry. This in wider terms translates to 22.5% of total methane emissions in the UK.

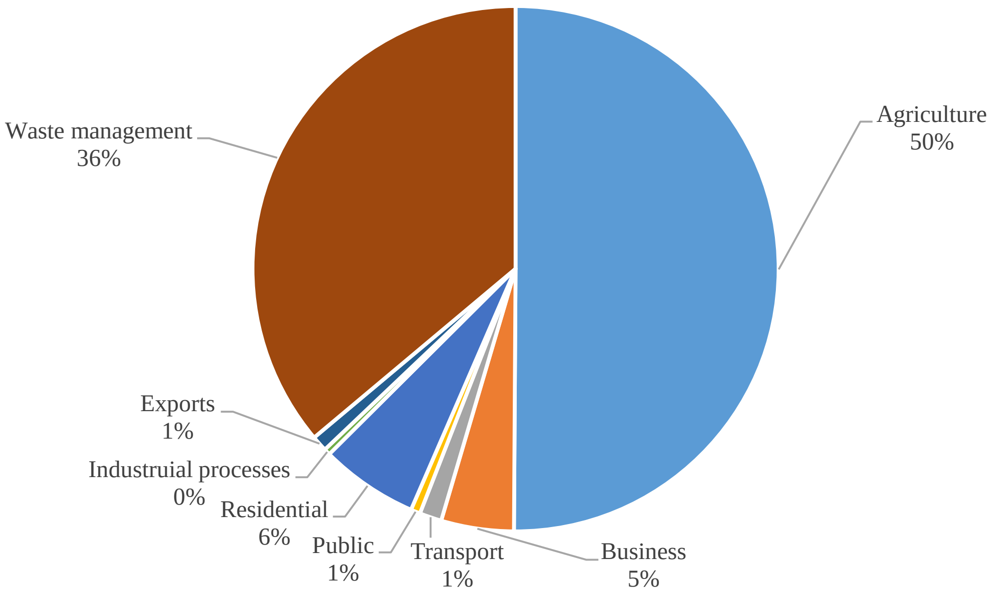


Figure 5. Methane emissions by sector in 2017 [110]

Methane can present an explosion risk at 5-15% content in the air [113]. There are numerous documented incidents where methane has been the result of gas fires and explosions in agriculture. For example, under certain conditions in which animals are fed a particular diet, this can result in the formation of bubbles containing methane in the slurry. The bubbles have been known to form a foam above the slurry which is susceptible to combustion [114].

4.1.4. Anaerobic digestion of manure as mitigation strategy for harmful emissions

The waste to energy conversion of manure to electricity, heat, fuel or grid gas is a four-stage process, as shown in Figure 6, consisting of hydrolysis, acidogenesis, acetogenesis and methanogenesis [115]. Manure feedstock is complex organic matter that consist of carbohydrates, proteins and fats. Through hydrolysis this is converted to soluble organic molecules such as sugars, amino acids and fatty acids. Acidogenesis or these components lead to the formation of volatile fatty acids, acetic acids, hydrogen and carbon dioxide. The volatile fatty acids is converted to acetic acids, hydrogen and carbon dioxide through acetogenesis. The last stage of the process is methanogenesis that forms biogas which can be converted into biomethane. Biogas is used at fuel in electricity and heating applications, while biomethane can be directed pumped into the national grid. Each stage the process is reliant on a number of microorganisms to participate in the reactions. Since this reaction occurs in an oxygen lean environment, there are less oxygen molecule to bind with the nitrogen molecules and form NOx.

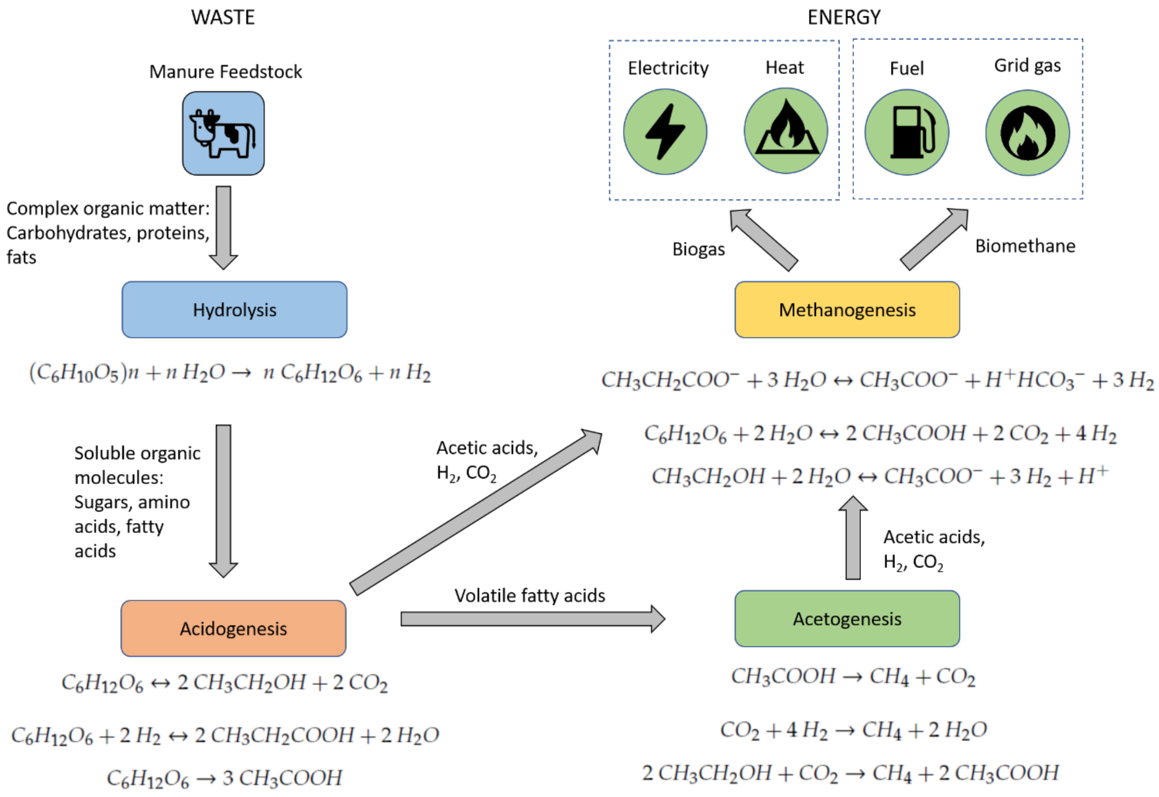


Figure 6. Waste-to Energy-process using manure as waste feedstock

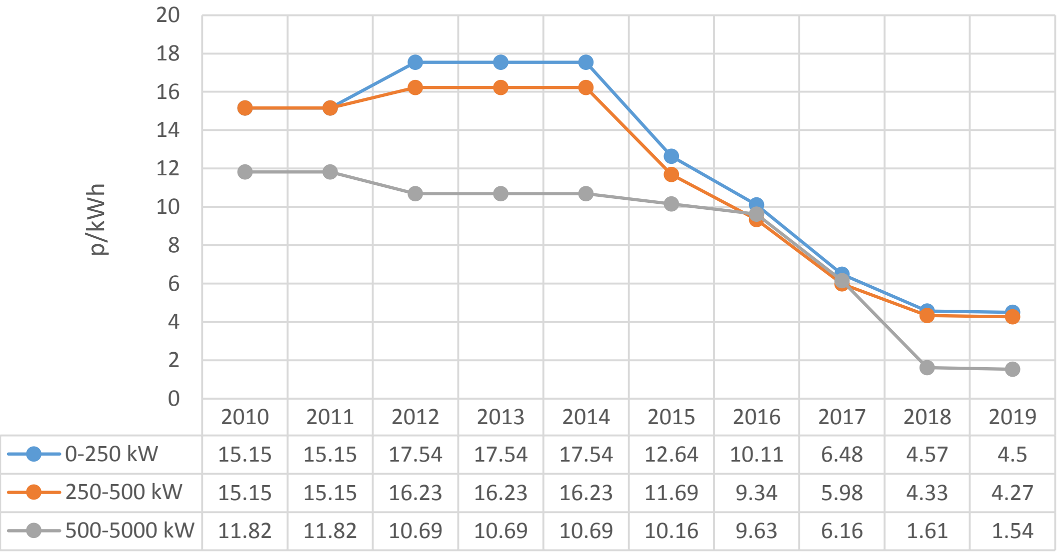
As highlighted, NOx formation is related to the degree of oxygen present when organic matter is decomposing, but when in an anaerobic environment, methane emissions increase. In the process of anaerobic digestion, this is ideal where the methane can be captured and used. In work produced by Sommer et al. [116], algorithms were developed for calculating methane and NO_x emissions from manure management [116], in which, the degree of emission reduction through anaerobic digestion was calculated. The model predicted 90% reduction of methane from outside stores with digested slurry. The digested slurry/muck is said to have a reduction of more than 50% of NO_x emissions after the application of the digested slurry onto agricultural land vs that of untreated slurry. No estimations were made regarding the effect on NH_3 production, where this is considered an anaerobic digestion inhibitor, through the change in pH. High toxicity levels also destroy microbes that produce methane [117].

For reduction in NH_3 emissions, it is clear that anaerobic digestion is not best suited to this. The addition of magnesium ammonium phosphate otherwise known as struvite is said to reduce NH_3 levels in a digester. Where struvite is a valuable plant nutrient source that slowly releases nitrogen and phosphorus overtime, it also known for its low solubility in water. Uludag-Demirer et al. [118] in an experiment added a set amount of struvite to a digester, resulting in 11% NH_3 reduction. Other work in this area also highlights the role pH plays, highlighting reactor conditions having a significant impact. Apart from optimizing reactor conditions and introducing additives, further processing would be the next cause of action. The anammox process is one such process aimed at post digested effluent. It is considered an efficient biological method for nitrogen removal through ammonium oxidization to nitrogen gas in anaerobic environment. Molinuevo's experiments [119] found that up to 92% of ammonium could be removed this way. As it can be quite costly to remove the NH_3, others look towards how the manure is applied to soil and if emission mitigation can be achieved there. Some of the main techniques from this aim towards limiting the mixing the slurry and muck have with the atmosphere through trail hoses and direct injection. The trail hoses limit the surface area that the muck and slurry is applied to. From Sommer and Hutchings [120], this is said to reduce the amount of emitted ammonia by 40%. For injection, this figure is said to be even higher at 60% when in combination of harrowing prior to the application.

4.2. Economical aspects of anaerobic digestion

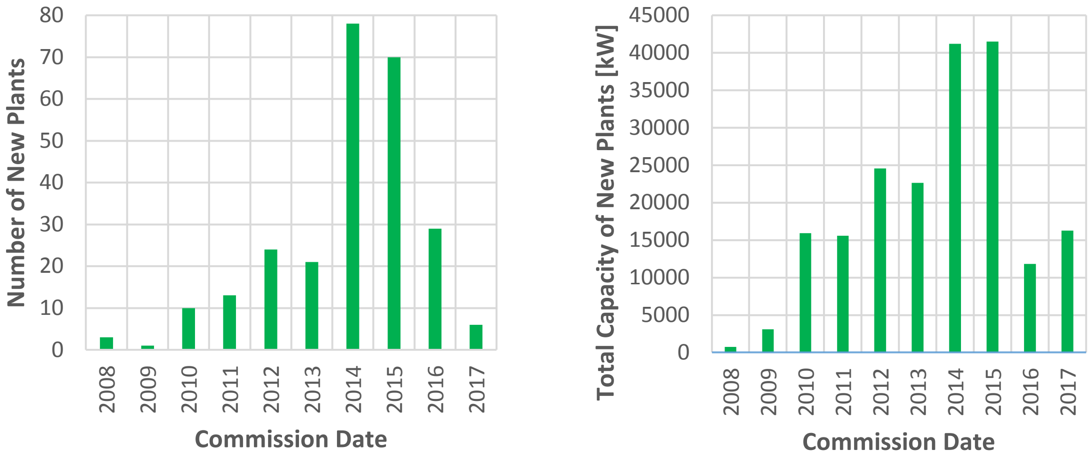
4.2.1. Current Incentives

As mentioned in the AD description, incentives have been on the decline at current, it can be assumed that almost all grants have been withdrawn by the government. Similarly, the tariffs in recent years have been reduced from 15.15 p/kWh in 2010 to 4.50 p/kWh in Jan 2019 for biodigester units less than 500 kW [121]. The gradual change in tariff rates for all sizes of AD is shown in Figure 7, offering a depiction of the decrease in the amount of government funds made available per year. The curves show the tariffs in p/kWh for three bands of installed capacity: 0-250 kW, 250-500 kW and 500-5000 kW. Some studies suggest that such change in tariff rates is too high for average size of UK farms and that lower boundaries should be introduced. Even incorporating the sale price tariffs, the cost viability particularly for small scale farm systems comes into question. This can be linked with the step decline seen in the number of AD plants commissioned each year. Where from the peak of 79 new plants commissioned in 2014 a fraction of that number is now commissioned which was only 6 in 2017 [122]. This is shown in a graph taken from Savills summary [123] on AD growth and performance depicted by Figure 8. A clear link can be seen between the drops in tariff rates from 2014 to 2015 shown in Figure 7 to the fall in plants commissioned per year shown in Figure 8.



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
0-250 kW	15.15	15.15	17.54	17.54	17.54	12.64	10.11	6.48	4.57	4.5
250-500 kW	15.15	15.15	16.23	16.23	16.23	11.69	9.34	5.98	4.33	4.27
500-5000 kW	11.82	11.82	10.69	10.69	10.69	10.16	9.63	6.16	1.61	1.54

Figure 7. Change in generation tariff rate for anaerobic digestion [121]



(a) (b)

Figure 8. Number of AD plants commissioned from 2008 to 2017 in UK (a) and the total capacity in kW (b) [123]

The numbers are very low considering the number of farms in the UK and goals set out by the DEFRA and National Farmers Union (NFU) aiming for 1000 on-farm AD plants by 2020 [124]. The actual number by 2020 will be considerably less highlighting the lag that this industry has to overcome if it were to pose a significant reduction in GHG emissions and averted emissions through methane capture pathways.

4.2.2. Capital Grants and Finance

The lag on the farm scale can be mostly put down to the capital costs required for installation. Almost all AD plants surveyed has some form of capital subsidy at 93% according to Bywater [90]. This is in part due to the financial status of smaller farms which can struggle to break even relaying on receiving farm payments from the government every year, making it unlikely that the capital would be available for such an investment. This lack of capital changes the use pathway of the methane gas, where expensive onsite gas cleaning and combustion in gas engines is not an option. Thus, the gas produced is merely used in boilers to heat farmhouses and to use for hot water, losing the potential for self-electricity generation and associated benefits. It is also worth noting that the tariff system changes onto the renewable heat incentive (RHI) as a result. A system not designed for this sector is providing yet a smaller insignificant income. Currently for small biogas combustion of which this pathway would fall under, the rate stands at 4.74 p/kWh as shown in Table 10, further lowering the economic prospects for farm AD.

Table 10. Tariff rates for RHI (small biogas combustion) [125]

Eligible Technology	Eligible Sizes	Accreditation Date	Tariff Rate 2019/20 (p/kWh)
Small Biogas Combustion	Less than 200 kWth	Before 1 April 2016	8.44
		Between 1 April and 30 June 2016	7.41
		Between 1 July and 30 September 2016	6.30
		Between 1 October and 31 December 2016	4.74
		Between 1 January and 31 March 2017	3.54

Between 1 April and 30 June 2017	3.37
Between 1 July 2017 and 21 May 2018	3.03
On or after 22 May 2018	4.74

4.2.3. Supply of slurry and muck

There is a high volume of slurry and muck produced on farms, where for instance, a pig unit near York with around 5000 pigs produces 20m^3 of slurry a day and over 1000 tonnes of muck each year. More can be said of the future with farm operations switching to fewer much larger operations, as small holdings with less than a couple hundred acers struggle financially with expensive farm machinery required to operate and the lack of land and livestock to spread overheads over. It is said that in the UK, 4.5 times as much derived organic matter is produced from farm operations (including slurry and muck) as from food, 90 million tonnes compared to 20 million tonnes [90]. Thus, the supply is not an issue.

4.3. Legislation controlling implementation of anaerobic digestion plants

4.3.1. Environmental Permitting

This is the primary means of regulating and minimizing the impact business activities have towards all environment aspects for England and Wales, such as to the air, water, land and considering factors like noise and safety. For AD plants to operate and spread digestate, a permit must be obtained. This involves completing a technical application form, demonstrating competency and willingness to abiding by the conditions of the proposed permit. Currently this can be achieved through Charted Institution of Wastes Management / Waste Management Industry Training and Advisory Board (CIWM/WAMITAB) scheme or Environmental Services Association / Energy and Utility (ESA/EU) sector skills. Setting out 3 different types of permits as shown in Table 11.

Table 11. Anaerobic digestion permits

Type	Description	Conditions
Exemption	For small scale plants which aren't waste facilities	• Must provide technical information to the environment agency and register • No charges • Only for agricultural businesses and burning of resultant biogas at the site. • 1,250 m^3 limit for the total amount of untreated and treated waste on site at any time • 0.4 MW limit for the thermal generating capacity of the plant • Minimum 28 days residence time of the waste [126]
Standard	For plants which can operate within a set of standardised rules and conditions.	• AD processing facility including the use of the biogas • 100 t processing limit per day • Combustion of biogas can be in gas engines, boilers, turbines, fuel cells or upgrading to bio methane [127]
Bespoke	For plants that cannot adhere to all pre-defined rules or conditions	The conditions vary considerably where both stationary and mobile AD plants are categorised for in this type. However, the flexibility of this type comes at more cost and time. Details can be found on the government website [128].

4.3.2. Permits for Spreading Digestate

As with exceptions to environmental permitting, digestate that is solely from agricultural waste streams is exempted from disposal charges provided that a number of conditions are met. These are:

- Only can be spread on agricultural land
- 50 t per hectare spreading limit
- 200 t storage limit at any one time
- Digestate must be from waste streams that improve or maintain the physical, chemical and biological properties of the soil to grow crops [129]

Note that material that has reached PAS 110 and Quality Protocol standards is no longer regarded as a waste. As such, the restrictions above no longer apply.

To spread waste material which does not meet the publicly available specification (PAS) 110 for agricultural and non-agricultural land for business or environmental enrichment, a permit is required. That is if the spreading activities to agricultural land exceed the exception conditions. Generally, a standard rule permit is given with the conditions and charges depicted in the government publication "SR2010 No.4: Mobile plant for land spreading" which specifies:

- A 250 t per hectare spreading limit
- 3,000 t limit for the amount of waste material on site at any time
- 12-month storage limit for the material
- For every spreading application of material to the land a charge must be payed depending on material type and the risk it poses, ranging from low, medium and high

High risk (Category 2) animal by-products (ABPs) cannot be used as feedstock in AD plants, unless they have been treated to a 133°C/3 bar/20-minute EU pressure-rendering standards [130]. Contrary to this manure is classified as a category 2 ABP, however, manure can be used without processing as raw material in an AD plant. But when mixed with ABPs such as catering waste the mixture must be rendered to the heat and pressure regulations prior to anaerobic digestion.

4.3.3. Planning Permission

Potential issues surrounding planning of AD plants revolve around 5 main concerns as highlighted from the governments planning policy statements and supplementary planning guidance [131]. These are:

Site Selection. The AD reactor tank can sometimes be quite large presenting a significant change to a landscape, where tanks can reach as high as 15 m. However small on farm digesters can sometimes be accommodated within the farmyard and buildings concealing it to an extent. Where this may not be possible, in the interest of reducing tank visibility, it can be somewhat burried in the ground reducing the visual impact. The burial also offers heat insulation benefits. Centralised AD plants have issue of the transport of feedstock involved, affecting chances of approval, giving on-farm plants the advantage.

Feed Stocks and Product Storage. Planning permission may be given only for specific feedstock, adding to or changing the feedstock is not allowed without further planning consent. This ties in with the exception permit given to farms that by adding other feed stocks it can lead to the exception being revoked. The storage of slurry and muck used in on-farm AD plants is covered by the water resources (control of pollution) (silage, slurry and agricultural fuel oil) England regulations and the nitrates directive (91 / 676 /EEC). Specifying the minimum standards for construction related to the design and operation of any farm slurry storage system.

Odour. AD by its nature of breaking down organic matter is an odorous process, this is of concern. Where predicted odour effects and proposed mitigating measures should be reviewed. If a location is considered to be sensitive to odours, information on the control measures should be provided from the developer to ensure that all sources are accounted for. Farms are already known for to be odorous and thus odour concerns are lessened to those of centralized facilities.

Emissions to Ground and Water Courses. As has been made clear in previous section, the runoff from raw agricultural wastes such as manure and slurry can contribute to serious farm pollution incidents. Therefore, the AD of farm waste should be conducted in a manor to reduce the likelihood and ability of the material to pollute water sources. In many application cases, the requirement of a bound wall is put forward by the planning authorities to prevent effluent spillage in the event of a leak. As for ground water leaking, the surround surface of a supposed plant is usually required to be concreted and run off prevented from reaching normal drains. Delays in the planning process can be the result of concerns in regard to designs inadequacies.

Emissions to Air. The production of biogas from AD and its uses contributes to a number of emissions to the atmosphere, manly from engine exhausts, gas vents and flare stacks. The emissions can however be considered insignificant provided the equipment meets design specifications and is routinely serviced. For larger on-farm and centralised AD plants integrated pollution control measures are required to control the emissions to meet regulations.

4.4. Implementation of anaerobic digestion to farms

4.4.1. Slurry and Manure as a Feedstock

Without adding other feedstock, the AD of slurry and manure has been proven to be uneconomical for both on farm and centralized plants due to the low gas yields, high capital cost and absence of gate fee. The legislation also plays a large role here in the restrictions placed on the exception type permit for farm-based plants. Other wastes such as those from grain processing can be added to increase gas yield without increasing the potential environment effects. In surveys conducted in 2017, it was reported that there were 401 AD plants in the UK, if those for treating sewage sludge are ignored, with more than half at 221 utilizing slurry and manure as feedstock. However, those dedicated to only slurry and manure are uncommon making up just 6% equating to 24 plants, with the capacity of processing 165,000 tonnes per year [132].

4.4.2. Grid Connection Issues

For widespread implementation of AD to farms, significant issues can be expected in connecting to the grid in part due to the low load electricity lines supplying many farms and the power of transformer. If the national grid deems the transformer inadequate, this can make the implementation of an AD plant to produce electricity not economically viable. Because it is presumed that small AD plants are unlikely to produce significant extra electricity that can be sold to the grid.

4.4.3. Lack of Land

From the regulations on digestate spreading where 50 tonnes per hectare is the spreading limit, large livestock farms particularly those where the animals are kept indoors all year round and have little in terms of land can be a significant issue. On the contrary these farms must find ways to get rid of slurry and muck like the straw-muck exchange highlighted in the feedstock preliminary section. And if this were to be replaced by digestate the application rates are the same. If PAS 110 and Quality Protocol standards are achievable, converting slurry and manure to digestate would be very advantageous for surpassing the application limits.

4.4.4. Technology

If widespread implementation were possible this could see a significant contribution to the UK's energy demands if the majority of manure and slurry were to be processed. This amounts to 90-100 million tonnes of agricultural by-products such as manure and slurry available each year in the UK. This is based on a 20 m^3/t (8% dry matter) average gas yield of slurry, that 1.7 kWh of electricity is produced per $1m^3$ of gas due to conversion losses and if 50% of the available manure/slurry can be processed, 1.615 TWh worth of electricity could be produced. A reasonable estimation which could provide 0.45% of the UK's annual demand, based on 2018 at 352.064 TWh [133]. A low percentage, but after considerations of the useful heat that can be harvested alongside the emission mitigations, it becomes more considerable. But the low electricity generation is a limiting factor in the technology potential.

4.4.5. Operation

The success of an on-farm AD plant, no matter how good the design nor technology, is inevitably comes down to operator skills, frequent monitoring and feeding the digester. On many farms, the muck and slurry are required to be mixed into the digester at a certain ratio for instance. Adding to this AD's can be plagued by a number of problems namely:

- Frothing
- Acidification
- Increasing viscosity
- Increasing volatile fatty acids (VFA) and total inorganic carbon (TIC) value
- Poor methane yield

These problems, if not corrected and kept on top off, can lead to poor biogas yield. Frothing alone can reduce biogas yield by up to 20% [134], with the cause linked to the constitution of the digestant and mixing routines within the reactor tank. These problems make time allocation and training a must for the farmer/operator. As such, a best practice guide should be made available if not already on the operation of AD plants specific to slurry and manure.

4.4.6. Bespoke cases

One size does not fit all in the case of widespread farm implementation, every farm is individual and presents its own challenges. The differences from farm to farm can be enormous from the amount of slurry and muck produced, to the characteristics of the feedstock and the planning complications. At a government level to seek to drastically increase the number of on-farm AD plants, this would prove complex as what may be beneficial to one may be inadequate to another.

Here, we provide two cases of commissioning of anaerobic digesters, which use manure as a feedstock. The first case is the Copys Green Farm located in Wighton, Wells-next-the-Sea in the eastern part of the UK, as shown in Table 12. The farm is very much sustainability driven and owners won a number of awards for doing so, namely the Farmers' Weekly green energy farmer of the year 2010. Note that £100,000 grant from bioenergy was turned down due to stopping double Renewable Obligation Certificate / Feed-in Tariff (ROCs/FIT) from being revived. Payback period was estimated at 8 years with a £83,000/year running cost most of which was the high energy feedstock. The biogas was produced at the rate of 70 m^3/hr burned to generate 131 KVA for grid export. In the planning and development stage the biggest barriers to on-farm AD is described as administrative. This includes the environment agency and OFGEM paperwork, where the owner feels the paperwork is disproportionate to the risk.

Table 12. Summarised data of Copys Green Farm [90]

Digester Size	870 m^3 (mid to large size)
Digester Type	Mesophilic, insulated, steel glass coasted tank with fixed roof
Gas Use	140 kW CHP, Feed in tariffs, extra heat used in grain drying, cheese making, dairy hot water and heating the farmhouse.
Commissioned	2009
Feedstock (tonnes per year)	Slurry from 100 dairy cows estimated at 2,500T/yr, Maize Silage or fodder beet estimated at 2,500T/yr, Whey from cheese making supposed feed stock to be incorporated but not yet would be around 210T/yr

Farm Size	230ha, arable and dairy, all in NVZ (Nitrate Vulnerable Zone)
Capital cost	Estimated to be £750,000, self-financed, with £100,000 capital grant turned down.
Issues	Unreliability of CHP. Tech provider issues (takeover midway through project)
Barriers to AD	Administrative: EA and OFGEM paperwork
Advantages	Recycling and improved utilisation of crop nutrients. Reducing risks the manures pose to NVZ area as digestate

The second case is a Woodhead farm located near Annan in Dumfries and Galloway in the western part of the UK, as shown in Table 13. A SlurryGen-50 digester was installed by Advanced Anaerobics Ltd. to help reduce electric bill and generate income [135]. 500 kWh is used each day of the total 1,200 kWh produced with the balance exported to the grid. Owners applied for the feed in tariff in 2014 securing 12.46 p/kWh. The excess heat is planned to be used on farm and generate additional income through RHI scheme. With these tariffs and savings to the electricity bill, payback period is estimated 60 months (5 years). It is said that for each ton of dry organic matter in slurry can produce 300-400 m3 of biogas. Operating cost is highlighted as an issue in this case study, because for example the CHP generator requires routine maintenance and periodic engine rebuilds. Over a 20-year lifetime, the operating costs of the plant as a whole will exceed the initial capital cost.

The Farmers' Weekly points out that in 2015 only 18 slurry AD plants were running in the UK. There were however 20-30 units at the planning stage. More widely 280 on-farm plants have been encouraged with RHI and FIT's.

Table 13. Summarised data of Woodhead farm [135]

Digester Size	Small
Digester Type	Mesophilic, insulated, steel glass coasted tank with fixed roof
Gas Use	50 kW CHP, some used on farm, rest exported to grid through feed-in tariff. Surplus heat planned to be used on farm under RHI
Commissioned	2015
Feedstock (tonnes per year)	Slurry from 320 dairy cows estimated at 24 T/day
Farm Size	n/a
Capital cost	Estimated to be £400,000 (self-financed)
Issues	Operating cost due to small plant
Barriers to AD	Administrative: EA and OFGEM paperwork
Advantages	Smaller size, simplified planning and permits, as does not need crop or other material brought in, there is no requirement to qualify as consented waste management site and lower capital cost.

4.5. Summary of manure and AD implementation

Manure and slurry present significant anthropogenic emissions of NH_3, NO_X and methane in the UK at 40%, 28% and 22.5% respectively. This requires that anaerobic digestion mitigations of 90% in methane from stores and 50% in NO_X emission after the application to land can be achieved. However, AD has poor NH_3 reduction capabilities, requiring extra processing. Although a more effective migration pathway may be to change how muck and slurry are applied to land, a reduction of up to 40% is achievable by minimizing aeration.

Sharp drops in tariff rates, high capital requirements and lack of grants make the economic side of AD an issue. On-farm AD has been named numerously as the most suitable type for manure but the least viable. Therefore, reforms to the incentives are a must if the number of AD plants are to increase in the UK, especially on-farm types which rely on grants. As the current tariff banding system is unsuitable for on-farm AD, implementing higher paying bands would be advised. A gate fee for processing, which includes the cost of opening, maintaining and eventually closing the site and also may include taxes applicable in a region, would also be advised to reduce dependence on biogas yield and temptations of using high energy crops.

Legislation and planning play a key role in the establishment of farm digesters with exception permits designed for this scenario, but for an exception to be grated strict rules apply. For more normal or unique operations, two other permit types (a standard rule permit SR2010 and a planning permit) can be granted at a cost and more time. The quality of the digestate is key in what can be done with it and how much can be applied to agricultural land. For use on non-agricultural land digestate incurres charges, limitations of quality and permitting (if still a waste). Manure is also found to be categorized as a high-risk waste which presents pressure and heat rendering incursions. These can however be ignored provided it is not mixed with other animal by-products. Overall, the legislation can be said to be well founded and necessary. Planning permission for many is where issues arise in legislation delaying a project or preventing its construction. The case studies show legislation is a barrier to AD. But as the planning difficulties are routed in reducing the risk an AD plant poses to the surrounding environment, no changes are envisaged as to ease the implementation of wide spread AD plants, with the environment as one of the primary focuses of this paper.

A significant amount of electricity could be produced, at 1.615 TWh equivalent to 0.45% of total UK's annual demand. Potential grid connection issues can limit this but for small on-farm plants encouraged in this report it can be said to be minimal, with the majority of the useful energy used onsite. Furthermore, the bespoke requirements for on-farm AD are known to present difficulties for the widespread implementation. Finally, as stated, inevitably the success of an AD plant comes down to operation. Improper monitoring and lack of know-how can lead to poor gas yields through problems common to digesters. Therefore, training and courses on operation are a must not just to prove competency for attaining permits but also for good operating practice.

5. Conclusions

Waste-to-energy sector is well developed with a number of processes capable of dealing with a variety of waste streams for energy and product extraction, improving sustainability and waste management, critically displacing fossil fuels and transferring towards a circular economy. However, challenges remain in the effective implementation of these processes in the UK. From the existing body of studies, it is clear that no 'quick fix solution' will guarantee energy sector decarbonisation. Conventional bioenergy's capacity to produce significant GHG reductions is being constantly debated. Sustainable residues and waste from biomass may and should definitely be part of this solution. This review has focused on certain waste streams such as biomass residue and agricultural waste, landfill waste, food waste, fats-oils-grease, wastewater sludge and manure, because they are considered potentially sustainable feedstocks. With a broad variety of current applications for several of these feedstocks, it will require strong environmental protections to avoid harmful environmental and social outcomes. Although the amount of such waste materials will be raised, it will decrease for certain wastes. Given the importance of several other applications, only a portion of the future flow of such resources can be devoted to the development of bioenergy. Of this among other purposes, there is substantial confusion regarding the exact quantities among energy values of the feedstocks that could be used sustainably of bioenergy development in the UK and further research on this is desperately required, taking into account economic forces, competitive applications, environmental imperatives and other considerations.

90 million tonnes of manure and slurry in the UK remain largely untapped, presenting the biggest contributions to ammonia, methane and nitrogen oxide anthropogenic emissions of any other

waste or industry in the UK at 40%, 22.5% and 28% respectively. With large scale implementation for on-farm AD, mitigations for 90% and 50% of methane and nitrogen oxide could be achieved with the added potential of generating more than 1.615 TWh of sustainable electricity. Further processing and changing application methods of slurry and muck to land is required to reduce ammonia emissions. Barriers in the form of insufficiently high banding and tariff systems, planning, high capital costs, lack of government subsidies and low gas yields prevent this. Therefore, it would be suggested that a lower high paying tariff banding system needs to be introduced to increase AD plants on farms. It is suggested an addition of a gate fee payment to reduce high energy crops used as supplements for gas yield, and to increase the amount of slurry and muck that are digested. The bespoke nature of farms could still present a fundamental issue in the degree manure and muck in the UK are processed.

The use of biomass capital to decarbonize the UK energy market has considerable potential, and the use of sustainable biomass waste and residues can be part of this solution, both in the direct processing of liquid and gaseous fuels as well as in the supply of renewable electricity generation capacity to decarbonize the UK grid and (indirectly) power a possible fleet of electric cars. Fostering the use of wastes and residues to create jobs in the UK also has considerable value. This is especially true for the AD industry where anaerobic digesters are widely distributed throughout the country, including in rural areas. There is also a need for the UK Government to step up measures to ensure efficient waste and residue production and we recommend a combination of responses including:

- Supporting effective EU policy reforms to promote a transition from traditional energy to sufficient advanced bioenergy from waste and residues;
- Formulating specific protections to follow the usage of waste and residues in the energy and transport field, notably in the absence of protections established at EU level as part of the existing Renewable Energy Directive adjustment procedure. A crucial precaution is the development of the required carbon accounting system for waste and residues, taking proper account of shifts in soil carbon supplies (e.g. in relation to straw extraction). The design of these protections will profit from cross-departmental collaboration to insure, in particular, that waste management priorities are not undermined;
- Research commissioning to enhance the perception of target applications for waste and pollutants, taking into consideration the business condition in the United Kingdom with regard to domestically accessible production and current applications (energy and non-energy). This would also create more accurate figures of the quantity of waste and contaminants that may be applicable to the energy and transport industry. Although we have established the feedstocks that currently tend to be more renewable, their processing into biofuels or biomethane might not be the more 'sustainable' usage, for example in terms of the total GHG emissions avoided;
- Cross-sectoral guidance on encouraging safe management and handling of waste and residues. Cooperation amongst policy departments collaborating on sectoral policies (agriculture, forestry, waste) and establishing targets for green energy and transport policies is required to ensure that policies in various sectors are complementary. It will result in valuable guidance to the various sectors and stakeholders and cause collaboration between, for example, producers, forest owners, waste processors and bioenergy or AD plant operators;
- Providing funding resources to develop emerging waste-to-energy processing technology. It would possibly involve capital funding for new projects, as well as help for current infrastructure growth. This would help increasing the potential of waste-to-energy processing and enjoy the advantages of technical innovation to reduce the costs of emerging technology.

Initiatives in these directions would be required not only to promote the development of an innovative waste-to - energy sector, but also to establish an acceptable route for the wider usage of bioenergy and biomass. There is an ability to reap several benefits by producing more green electricity, improving engineering know-how, and creating economic benefits like a large amount of potential jobs by turning waste and residue currently underutilised into beneficial uses. If protections are introduced, the environmental advantages of switching away from traditional biofuels in decarbonizing the UK energy and transport market would improve.

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Waste-to-energy conversion technologies in the UK: processes and barriers – a review

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Abstract: This paper reviews the sector of waste-to-energy looking at the main processes and feedstock involved. Within this, incineration, gasification, pyrolysis, anaerobic digestion and hydrothermal liquefaction are named and discussed. Through the discussions and scrutiny, manure is highlighted as a significant source of ammonia, methane, and nitrogen oxides emission, estimated to be 40%, 22.5% and 28% respectively of the total UK's anthropogenic emissions. Manure, and indeed the pollution it poses, are shown to remain largely ignored. In waste to energy processing, manure is capable of providing biogas for a number of pathways including electricity generation. Anaerobic digestion is highlighted as a suitable process with the crucial capability of drastically reducing the pollution potential of manure and slurry compared to no processing, with up to 90% reduction in methane and 50% reduction in nitrogen oxide emissions. If the majority of the 90 million tonnes of manure and slurry in the UK were to be processed through biogas harvesting, this could have the potential of producing more than 1.615 TWh of electricity. As such, the economics and legislation surrounding the implementation of anaerobic digestion for manure and slurry are discussed. In the end, restraining factors that limit the implementation of anaerobic digesters on farms in the UK are discussed. These are found to be mainly capital costs, lack of grants, insufficiently high tariff systems, rather than low gas yields from manure and slurry.

Keywords: waste feedstock; manure; anaerobic digestion; waste-to-energy

1. Introduction

The need to become more sustainable through the threat of global climate change and resource depletion is ever more prominent. Coupled with an ever-increasing population, rapid industrialisation, depleting fossil fuel resources present significant biowaste disposal and energy demand problems. In the UK, around 7.4 million tonnes of biodegradable municipal waste were sent to landfill in 2017 [1]. This waste could otherwise have been processed and recycled. The environmental impact of biodegradable waste extends beyond increasing greenhouse gasses due to the decomposition process. Untreated biodegradable waste release unpleasant odours due to decomposition and attracts scavenger animals and pests [2]. This has an impact on general public health and changes the biodiversity in the surrounding areas. Leaching from landfills not only contaminates the groundwater but can also affect the adjacent soil quality. In EU legislation, it is stipulated that biodegradable waste ending up at landfill must be reduced by 35% by 2020 compared to 1995 levels. This is one example of the driving forces behind waste to energy (WtE) processing, focused on reducing the volume of waste, recovering valuable products and producing electricity.

The term 'waste-to-energy' can be used interchangeably and encompass a variety of processes and technologies. The conversion of waste into energy will be analysed in this paper by the following processes: incineration, gasification, pyrolysis, anaerobic digestion, and hydrothermal liquefaction. The schematics of waste to energy processes are shown in Figure 1.

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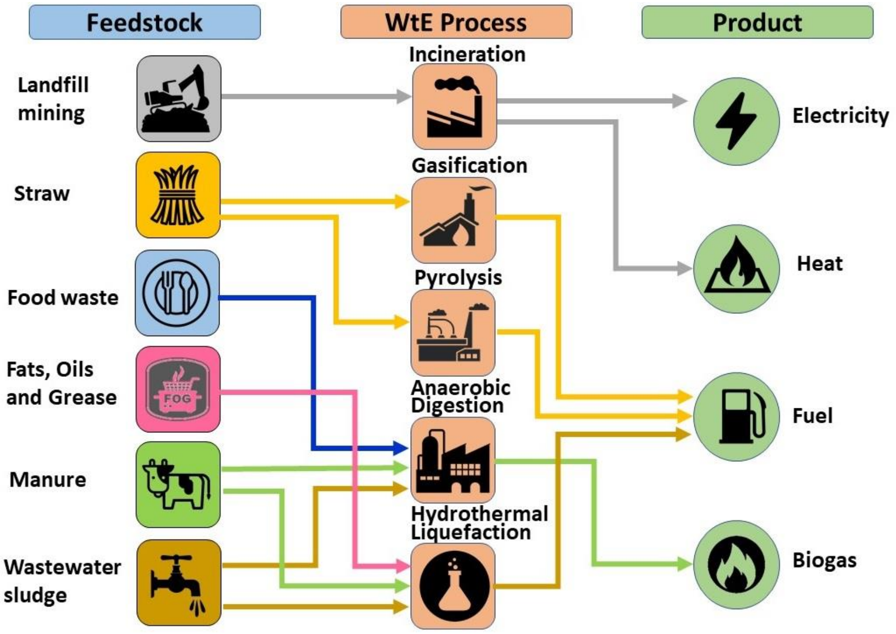

Figure 1. Schematics of waste-to-energy processes

Incineration is known as the complete oxidation within a waste stream of combustible materials and operates as temperatures above 850 °C. All feedstocks of waste addressed in this paper can be incinerated. This is one of the key advantages of incineration, the ability to deal with a diversity of wastes. Gasification in many sectors has been operating worldwide on a large basis for more than 80 years. During high temperatures (500 – 1800 °C), partial oxidation is accomplished by reducing the access to oxygen. The gases produced known as 'syngas' do not burn but can be gathered and processed for subsequent use. Pyrolysis operates similarly to gasification where partial oxidation is used to maintain thermal conditions. While this development is not new, a widespread deployment has not yet been accomplished. The process operates at about 300-700 °C. Anaerobic Digestion (AD) is an established process for the treatment of organic waste within the waste to energy sector. In 2007 the Department for Environment, Food and Rural Affairs recommended companies in England and Wales to use AD to better achieve electricity goals. Interest decreased because of concerns about economic viability. AD is still considered a key process for achieving a circular economy, increasing resource-efficiency and for the bioenergy-economy. Hydrothermal liquefaction is the thermochemical conversion of biomass into biocrude oil that can then be refined into petroleum derived fuels. The process is conducted in a 4 to 22 MPa pressurised environment at temperatures 250-374 °C. With promising biomass yields this process can become more widespread in the future in the waste-to-energy sector.

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The rise in WtE has contributed to energy recovery increases in the UK with tonnage of processed wastes up to 7.3 million in 2018, nearly 4 times that of 2014 at 1.9 million [1]. The estimated range of total biological waste in the UK in 2020, including forestry residue and sewage sludge waste streams, amounts to 406.86 PJ, as shown in Table 1.

Table 1. Summary of UK maximum estimates of potential for biological waste streams

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Waste stream	Petajoule [PJ]	Reference

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Renewable fraction of waste	43.7	[3]
Straw	132	[4]
	88.5	[5]
Food waste	46.9	[3]
	38	[4]
Green waste	10	[4]
Livestock manure	16.4	[3]
Sewage sludge	12.4	[3]
Used cooking oil	9.66	[4]
Forestry residues	8.3	[3]
	19.2	[6]
Arboricultural arisings	46	[3]
Landscape care wood	35.8	[6]
Total	406.86	

*1 Mtoe = 41.868 PJ

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Large amounts of waste are now processed at facilities capable of energy production. On top of this, wastes once discarded into landfills through enhanced landfill mining, can be dealt with past and present, altering previous perceptions of what a landfill is, considering them simply as ‘’temporary storage awaiting further processing’’ [7], with vast amounts of valuable materials and heavy metals that can be recovered. The waste generated worldwide is losing its potential contribution to sustainable living. Therefore, this paper looks to review the different wastes and the processes involved in WtE and assessing process capabilities and waste streams that can be incorporated. It also looks at the question on what more can be done and what if any significant waste streams remained untapped or not utilized to their full potential, how this can cause significant environmental and sustainable problems.

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This paper also emphasizes on manure that has great potential to be used as energy source in anaerobic digesters if implemented on small scales at local farms. A global concern is poor production and utilisation of nitrogen (N), phosphorus (P), and potassium (K) from livestock [8]. Organic matter and nutrients recycled in manure are essential for agricultural soil structure and nutrient content [9]. Manure has a natural nitrogen and phosphorus content so if it is not utilised as a fertiliser on agriculture, natural nutrient cycles are disrupted, possibly that nutrient leaching, so artificial fertiliser needs are generated. Nitrogen fertiliser processing requires extensive usage of natural gas and produces pollution that lead to global warming [10]. In addition, it is stated that existing usage of small phosphate supplies for phosphorus fertiliser is unsustainable [11]. Therefore, some issues may be mitigated by rising the use of artificial fertiliser by reusing manure.

On the other hand, the vast quantities of excreta produced in localised areas will add to the nutrient excess at the regional level [12]. Excessive use of manure as an organic fertiliser can contribute to soil and water eutrophication, pathogen transmission, air contamination, and greenhouse gas emissions [13]. Sustainable processing of these large units of output is only possible if manure is reused properly. Composting is a potential stabilising procedure. A significant drawback, though, is the strong nitrogen depletion. This phenomenon decreases the fertiliser benefit and may cause odour disturbance and present a serious environmental threat [14]. An option to eco-friendly treatment is anaerobic digestion (AD), which provides added advantage to restore the caloric content by biogas production. Unfortunately, manure 's strong nitrogen content is prohibitive to successful AD. Organic Nitrogen is transformed to ammonia through microbial degradation. Ammonia exerts a strong inhibitory influence on microbiological conversion at high concentrations. Non-dissociated free ammonia triggers the toxicity [15, 16]. This compound diffuses into cells, causing a proton imbalance or interfering with microorganisms' metabolic enzymes [17]. Overcoming ammonia inhibition is essential to effective manure AD.

To make this implementation feasible and sustainable, we have highlighted the need for further processing and changing application methods of slurry and muck to land as a requirement to reduce

ammonia, methane and NOx emissions. The paper also discusses the barriers in the form of inadequate high banding tariff and systems, planning, high capital costs, lack of government subsidies and low biogas yields. It has been suggested that a lower high-paying tariff banding system needs to be introduced to increase anaerobic digestion plants on farms. It is required addition of a gate fee payment to reduce the high energy crops use as supplements for biogas yield, and to increase the amount of slurry and muck that are digested. The paper also discusses the bespoke nature of anaerobic digesters on farms and the scales of anaerobic digestion plants. The value of this paper is that it has reviewed different challenges and aspects of implementation of anaerobic digestion systems on farms within a framework of waste-to-energy conversion.

In addition to technological and environmental prospects of WtE, previous studies also tried to understand social acceptance of wate to energy and renewable energy technology. Shackley et al. [18] performed work on carbon dioxide absorption and storage in Europe and found that most of the respondents accepted this issue under the regional CO_2 mitigation plan. Wolsink [19] points out that including local citizens in the policymaking phase would help strengthen the policies on social acceptance and that without societal recognition it is difficult to accomplish both waste-to - energy and sustainability targets. Social tolerance also has to be taken into consideration through decision formation. The three reasons for popular resistance to renewable energy technology were stated by Rogers et al. [20]: inadequate growth size, unreasonable cost-to-public benefit ratio and the lack of proper connexion between the local people and their views. Wang et al [21] analysed the waste management engagement in China, as well as how waste processing, sorting, collection, cost, age and education impact waste sorting satisfaction. They also examined the impact of satisfaction on participation in terms of enthusiasm, social contact and active involvement between region and gender by using systemic equation analysis from multiple communities.

To summarize what was mentioned above, we want to emphasize that this paper is a first attempt to look at the waste-to-energy that reviews the status of different WtE technologies in the UK, including the incineration, gasification, pyrolysis, anaerobic digestion and hydrothermal liquefaction. The reviews [1-6] mentioned above highlighted the expected amount of different types of waste in the UK that would be available by 2020 but did not specify the processes to treat these types of waste. The reviews [8-11] discussed the importance of using manure as an organic fertiliser and also the importance of pre-treatment of manure by using AD to avoid environmental impacts associated with soil and water eutrophication, pathogen transmission, air contamination, greenhouse gas emissions and overcoming the ammonia inhibition of AD processes [12-17]. However, these reviews did not discuss the potential barriers associated with the economic aspects of AD such as tariffs, incentives and implementation of AD in farms. Therefore, the aim of this review is to cover the current status of WtE in the UK, understand its limitations, advantages, environmental effects, identify challenges in regards to the implementation of the waste, and assess what can be done to further utilize waste to energy in the effort to reduce pollution, resolve waste disposal issues and address energy needs.

2. Sources of waste feedstock

There is a significant discussion on the sustainability of bioenergy in Europe and the United Kingdom in particular, sparked by the recognition that increasing bioenergy use has larger environmental and social effects than was previously expected. The effect of expanded crop production for bioenergy usage on land use and the implications for the bioenergy profile of greenhouse gas (GHG) are significant environmental concerns. Increasing global demand for main grains and other crops for bioenergy processing results in increased competition on global agriculture markets, which decreases food prices to differing degrees [22]. This coupled with land purchases from primarily subsistence farmers for the development of large-scale bioenergy crops is the primary source of worry over the social impacts of traditional bioenergy.

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The bioenergy produced from waste and residues is considered a way to boost environmental and social efficiency and industry credibility and to save more GHGs than conventional energy. Nonetheless, there are concerns about the viability of other feedstocks and the amounts of biomass accessible to the bioenergy industry as a feedstock. Considering that the UK energy market must be decarbonized, it is important to consider 1) possible domestic waste and residue that can help minimise the effect of UK biofuel use on biologically, socially and economically, including the ILUC impacts from outside the UK; 2) sustainable waste and residue amounts that could be required in advanced processing of biofuel; 3) the growth of job opportunities in the United Kingdom as a consequence of setting up a bioenergy industry in sustainable development.

2.1 Biomass waste

The efficient use of biomass waste offers an extensive range of advantages. Apart from fulfilling the requirements of public services, biomass can be a tap alternative sources of carbon and play a key role in a production energy system using renewable sources without decreasing food and feed stocks. There exists a great variety of biomass waste that can be used for bioenergy production. One common type is straw, which is a by-product of the cereals harvest, but the definition may be further specified to include oil-seed rape grain and maize-growing 'substantive.' There are a variety of common applications both in the farming industry and beyond. The large-scale usage as field improvement, livestock bedding and the substitute for fodder are significant applications in the UK. Straw is also used for mushroom and horticultural production. Apart from growing, straw is used as stalk and more commonly as a building medium and for direct combustion for heat and electricity production.

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As a bioenergy feedstock, the sustainability of straw is highly linked to its scale, its location and removal from current applications which can benefit from their own impact. Kretschmer et al [22] address the potential for European straw usage as well as the adverse effects of excessive straw diversion on energy usage, including: the degraded capacity of the soil, particularly through a reduction of organic soil content and consequently of nutrients; potential long lasting impacts on fauna arising from shifts in stubble heights and straw control and impact on livestock health because there is no readily accessible option to roughage and bedding (like sawdust or wood chipping). For 2020, multiple reports forecast the availability and order of straw for different purposes. As Table 1 shows, the results vary greatly. One potential explanation is the challenge of taking into account regional differences. Depending on these reports, the amount of 18 to 132 PJ of straw for UK bioenergy output was predicted for 2020 by Smith [4]. The UK's straw capacity is 88.5 PJ from a European report that offers forecasts for different countries [5].

Another type of biomass waste is woody residues. Smith [4] stated that most of the UK 's new forestry (roundwoods and residues) products were recycled into the sawmill industry and the panelboard industry. Given the high proportions of (mostly private) under management forests in the UK, however, the supply of residues is likely to increase significantly, with certain materials available for the energy sector as a feedstock. It may have positive side consequences, such as providing local work, which also contribute to habitat upgrades. Increasing the production of forestry residues by better management was one of the specified goals of the new forestry policies and strategies of the UK, in particular the Woodfuel Strategy and the Woodfuel Implementation Plan 2011-2014 of the Forestry Commission. It is expected to produce another two million renewable tonnes (residue and plant) of wood biomass each year by 2020 by: 1) Setting requirements for a profitable and safe wood fuel supply chain; 2) Capacity building by market growth and reduction of obstacles to forest management; 3) Ensure that, in close collaboration with the Biomass Energy Center (BEC), access to specialist expertise leads to business growth.

2.2~~1~~. Landfill mining

This feedstock is the result of landfills ‘reopening’ to be extracted of their sources of valuable and combustible material wastes. As landfills are known to incorporate a large degree of different wastes, the exact chemical constitution can vary considerably. Prior to the European directive in 2001, there was little control in the way of what ended up in landfill sites, giving rise to concerns of hazardous wastes and indeed the effects to the environment [23]. That said typically plastics, organic wastes, different kinds of metals, textiles, wood and rubber are most commonly found in the feedstock based on the combinations of waste ending up at landfill. Table 2 gives a brief outline of

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these sources. These main raw materials may be mixed in with contaminates containing elements such as sulphur, chlorine and heavy metals. Bosmans et al. [7] showed that the presence of these elements can greatly affect the quality of the products produced though waste valorisation such as the syngas, bottom ash, fly ash, digestate and vitrified slag. Increasing the need of specialized abatement technologies required to reduce the amount of pollutants in the products or emissions to the atmosphere. These technologies take the form of flue gas cleaning systems.

Table 2. Different landfill waste streams

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Source	**Types of different waste streams**
Commercial and Industrial waste (CaIW)	Paper, packaging, metals, tyres, textiles and biomass [24]
Municipal Solid Waste (MSW) (Household waste)	Paper, cardboard, metals, textiles, organics
Refuse Derived Fuel (RDF) (processed CaIW and MSW)	Separation of recyclables, non-combustibles from source. Shredding/size reduction may include pelletizing. Processing done to adhere to a fuel specification.
Solid Recovered Fuel (SRF)	Similar to RDF but less contaminated and more homogenous, adheres to more stringent specifications [25]
Scrap Yard Shredder Residue (SYSR)	High degree of plastic and mixtures, metals, rubber glass, wood, leather, textile, dirt and grit. Mainly result of automotive scrappage [26]

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Note that the streams shown in Table 2 are in their own right different wastes that can be utilized for energy or product extraction if landfill is circumvented all together. Where Table 3 provides the typical properties that can be expected from MSW and RDF.

Table 3. Characteristics of MSW and RDF

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Source	% C	% H	% N	% O	% VM	Lower heating value (MJ/k~~K~~g)	% water	Ref
MSW	49.5	5.60	1.33	32.4	87.1	18.7	34.2	[7]
	35.8	4.8	0.78	24.3	67	15.2	32.4	[27]
	43.71	7.73	1.95	37.66	77.66	18.5	20	[28]
RDF	54.6	8.37	0.91	34.4	88.5	22.6	10.8	[7]
	48.2	6.4	1.22	28.4	75.9	17.8	20	[29]
	48.5	6.4	1.2	31.3	83.5	20.9	26.51	[30]
RDF (From landfill)	54.9	7.38	2.03	NA	80.4	22	14.4	[7]

2.3~~2~~. Food waste

The definition of food waste is taken from Lebersorger and Scheinder [31] where it includes solid components from food preparation residues, post-preparation and consumption residues, part consumed food and whole unused food. The main sectors according to Skaggs et al. [32] from which this waste arises are firstly industrial food processing centres; secondly, institutions such as hospitals, universities, schools, prisons; thirdly, commercial enterprises such as restaurants, grocery stores,

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food distribution centres; and fourthly residential units. A degree of this waste is averted through a food waste recovery hierarchy before the level of energy and product extraction. This type of waste is known to be of high value in its uncontaminated state where a large part at the industrial level waste can be used to create animal feeds. The types different from the animal feeds are opened up to energy and combustible product extraction and through anaerobic digestion. Looking at published work, generally speaking, the degree to which the feedstock is valued revolves around the moisture content [33,34,35]. Where a lower moisture content increases the combustion characteristics and suitability to associated processes, also reduces energy loss through steam/drying. A higher moisture content increases suitability for digestion. Table 4 shows typical composition of food waste in UK.

Table 4. Characteristics of typical food waste

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Source	% C*	% H*	% N*	% O*	% VM* Of TM	Higher heating value (HHV) (MJ/k~~K~~g)	% Lipid	% Protein	% Carb	Ref
UK	52	6.9	3.1	38	22	22	15	21	48	[36]
Korea	51.2	7.2	2.9	38.1	-	-	-	-	-	[37]
Various	-	-	-	-	-	-	6.4-24.1	3.9-21.8	24-46.1	[38]
Malaysia	47.4	6.9	3.3	38.7	-	17.45	-	-	-	[39]

2.4~~3~~. Fats, Oils and Grease (FOG)

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Large institutional kitchens, restaurants, cafeterias are responsible for the production of waste/used oils, fats from animals and grease through cooking. A percentage of this waste inevitably ends up down sinks and in the sewers whereas they are non-water soluble can collect and form blockages. The Environmental Protection Agency (EPA) has estimated FOG build ups contribute to 70% of sewer pipe blockages and 30% of pump station failures [40]. Water UK [41] provides guidance on avoiding fats and oils from entering the sewers for large kitchens where grease traps are the primary means of capture. This works via taking advantage of the difference in density of water and FOG to capture and contain the grease to be disposed. This grease can contain a wide range of suspended waste food solids and wastewater, and as such, is known as 'brown grease'. These contaminates make it more difficult to recycle than 'yellow grease' which is from spent oils and fats that have not interacted with wastewater i.e. deep fat frying. Due to this contamination, the brown grease is not used for biodiesel production due to lower energy content of 35 MJ/kg compared to 40 MJ/kg of waste cooking oil. [42]. So, the brown grease is usually disposed as waste rather than recycled into energy. There are many options in regards to utilizing yellow grease in anaerobic digestion, composting, processing into biodiesel as mentioned, or used as additives for animal feed and soap. But the uses of brown grease are not so clear with its hazardous classification and more difficult extraction procedures.

Other than waste oils, fats and grease from the cooking industry, a large amount of synthetic and mineral oil wastes accumulate when they are no longer deemed fit for purpose. These are motor oils, heating oils, hydraulic oils, ship oils, sump residue and oil-water emulsions. All categorized as hazardous waste due to the chemical makeups used. For example, used engine oil contains cocktail of hydrocarbons, heavy metals (magnesium, cobalt, zinc, iron), minerals, chlorine, sulphur, phosphorus, nitrogen and additives all known to have cancerous effects and detrimental to the environment [43]. The environment protection agency states that one drop of used motor oil can contaminate 1 cm^3 of water, highlighting the scale of potential cause when considering if all vehicles that have internal combustion engines produce waste oils.

2.5~~4~~. *Wastewater sludge (WWS)*

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During the processing and treatment of wastewater to return it to the environment, a residual nutrient rich semi-solid is produced known as wastewater sludge (WWS), typically containing 25-75% solid based on weight. WWS can be composed of solids from primary and secondary treatment stages. During the primary stage, the initial suspended solids within the wastewater are separated. Around 40-70% of solids within the wastewater are captured, where the organic and inorganic fines are concentrated down to 2-7% and 60-85% for volatile suspended solids. Secondary treatment stage focusses on biological aspects where a combination of aeration, exposure, microbes and secondary settling occurs. Solids are concentrated to 0.5-1.5% with volatile suspended solids concentrations at 70-80% [32]. Biochemical characteristics of primary and secondary sludge are shown in Table 5.

In the US approximately 6.3 million metric tons of municipal WWS was produced in 1998 of dry solid weight (according to the US environment protection agency) and todays figure will only be higher. When processed properly it can be very beneficial for the application of agricultural land to improve soil quality, using as a soil conditioner in landscaping, and using for part of landfill cover-ups [44]. Hence the term 'biosolids' is associated with processed WWS. The main energy recovery process associated with WWS is anaerobic digestion, in which the resultant bio-waste and indeed the treated WWS can be used in the production of biosolids for fertilizer. However, there are social concerns in regards to heavy metals and pharmaceutical compounds that could be within the WSS. Which, when introduced to agricultural cropping soils can give a predominately negative effect on local water, energy and material sustainability [45]. In addition to affecting the ecosystem through concentration of heavy metals, crucially highlighting contaminates play negative role in reducing the sustainability and product quality. An option that reroutes the biosolids from being used as fertilizers and averting the social concerns is hydrothermal liquefaction processing into bio crude oil. This bio crude oil can then be refined to meet bio diesel and diesel standards [46].

Table 5. Biochemical characteristics of primary and secondary sludge

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Source	% C	% H	% N	% O	% VM	HHV (MJ/k~~K~~g)	% Lipid	% Protein	% Carb	Ref
Primary sludge	47.8	6.5	3.64	33.6	82.17	20.7	-	-	-	[47]
	51.5	7.0	4.5	35.5	65	-	18	24	16	[48]
Secondary sludge	43.6	6.55	7.9	29.0	76.25	19.6	-	-	-	[47]
	52.5	6.0	7.5	33.0	67	-	8	36	17	[48]

2.6~~5~~. *Manure*

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This is the combination of animal faeces with an agricultural by product such as straw (used as animal bedding). All livestock, particularly indoor bred stock produce manure. This manure can vary in composition depending on the type of animal it is from and what diet they are on. Table 6 shows these differences in the biochemical characteristics.

Table 6. Characteristics of different manures at 76.37% water content

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Source	% C	% H	% N	% O	% VM	HHV (MJ/k~~K~~g)	% Lipid	% Protein	% Carb	Ref
Fattened cattle	35.38	3.73	2.38	57.51	16.21	15.16	6.8	26.6	52.5	[32]
Dairy cows	38.8	5.1	1.3	54.7	83.2	11.9	5	18.11	52.6	[32]

Bacon pigs	41.1	5.42	3.36	50.1	83.7	-	20.3	24.5	34.7	[32]

Fertilization is the primary use for this type of fully biodegradable waste where without any processing it is spread onto crop producing land. A common life cycle is known to be set up between arable and livestock farmers in the UK as a result where manure is exchanged for straw. Where the manure is desirable for arable farmers to fertilize their land and the straw from the crops produced by the arable can provide a bedding and food source for a livestock farmer [49]. This is the virtually at present the only pathway for disposing the manure and slurry. Processes such as anaerobic digestion (discussed in the next section) aim to tap into the vast amount of energy stored within this feed though emitted products. Nitrous oxides, methane and ammonia are the most prevalent gasses released into the atmosphere by the decomposing manure without any process intervention. This is of great concern given the amount of manure produced every year and known the global warming characteristics of said gasses. The animal agriculture sector accounts for 37% and 64% of the annual anthropogenic methane and nitrogen oxides emissions, respectively, which are 23 and 296 times the global warming potential (GWP) of carbon dioxide. In addition, livestock are responsible for 64% of the anthropogenic ammonia emissions, contributing to the formation of acid rain and acidification of ecosystems [50]. Such high percentages are alarming considering that the majority of these emissions are from manure and slurry and highlight the need for processing to bring emissions in the sector to some acceptable level.

3. Waste-to-Energy Processes

Waste-to-energy encompasses a variety of specific methods and technologies. In the purposes of this article, this is intended to identify a variety of disposal methods and techniques utilised to produce a functional source of energy and to minimise the amount of residual waste. Such energy may be in the form of power, heating and/or cooling, or turning the waste into a product for potential usage, such as biogas, automotive fuels, or a mixture of these types. In this paper we will review the conversion of waste to energy through the following processes: incineration, gasification, pyrolysis, anaerobic digestion, and hydrothermal liquefaction.

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3.1. Incineration

Incineration is classified as the full oxidation of the combustible materials within a waste stream. The process is composed of several key stages of drying/degassing, pyrolysis and gasification then combustion. Unlike other processes in this list that only partially oxidize the waste stream, incineration can be fed by a large variety of waste streams. In fact, all waste streams discussed in this paper can be incinerated. This is one of the main advantages incineration has, the ability to deal with a high degree of waste variety. The variety effects the product percentages left after processing, such as the bottom ash which in MSW incinerators is approximately 25-30 % by weigh of dry waste input, and the fly ash is at 1-5 %. The fly ash requires immobilization to be made environmentally safe, which can then be used in asphalt concrete. The bottom ash however requires much more processing, where at a slag reprocessing pilot plant facility, valuable metals (Al, Fe, Cu) can be recovered. The residue after metal recovery can then be granulated for the construction industry [51]. Figure 2 is an example diagram of a combined heat and power (CHP) plant based on incineration.

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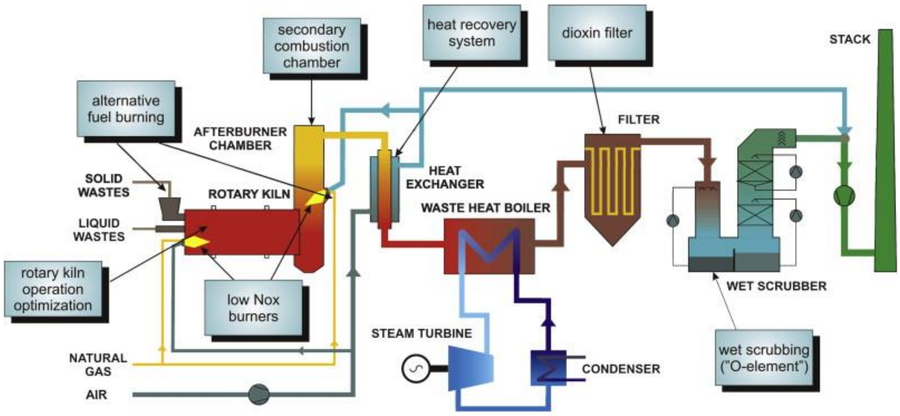

Figure 2. Simplified layout of a waste-to-energy incinerator [51]

Originally, incineration was purely used to reduce the volume of waste as well as destroy harmful substances in the effort to prevent health threats. Now, waste incineration is predominantly combined with energy recovery the importance of which is increasing. Denmark and Sweden are notably the world leaders having produced electricity from the incineration of waste for more than 100 years [52]. Now there are 3 main types of incinerators; gate, rotary kilns and fluidized beds, each type specified for particular feedstock. The plant efficiency factor of these incinerators according to the confederation of European WtE plants (CEWEP) in 2010 based on accounted 314 plants was at average 0.69. The specific electricity produced as weighted average was 14.89% of total Mg and heat at 34.59% of total Mg [53]. Note that the Plant Efficiency Factor ($R1$) in the equation (1) was used to obtain the figures given in accordance with the waste frame directive [54]. WtE plants "producing electricity only" have the lowest $R1$ factor of 0.55, as a non-weighted average, so that only 37.3% plants reach $R1 \geq 0.60$. Although WtE plants "producing heat only" have a higher $R1$ factor of 0.64, as a non-weighted average, only 68.1% plants reach R1 ≥ 0.60. In this case, the import of the total amount of electricity to treat the waste has a negative influence. WtE plants "CHP producing" achieve the highest $R1$ factor of 0.76, as a non-weighted average, so that 77.2% plants reach $R1 \geq 0.60$.

$$R1 = \frac{(E_p - (E_f + E_i)}{\left(0.97 \cdot \left(E_w + E_f\right)\right)} \tag{1}$$

where, $R1$ - plant efficiency factor, E_p - annual energy produced as heat or electricity, E_w - annual energy contained in the treated waste, E_i - annual energy imported, and E_f - annual energy input to the system from fuels contributing to the production of steam [53]. These plants are notably still less efficient than conventional power plants. This is in part due to specific equipment requirements for incineration of waste, limitations on steam pressures due to corrosion risks, energy requirements to maintain optimal operational regime and critically pollution control equipment necessary to treat flue gasses. Generally, the more effective and complex a pollution control system is the higher the energy needs.

The current status of this technology in the UK is at TRL 9 since the actual system is proven in an operational environment. In 2016 there were 115 incineration facilities in the UK. It is estimated that 6.1% of waste generated in the UK is processed through incineration [55, 56]. 37 incineration facilities were fitted for energy recovery accounting for 3.4% of waste processing, as shown in Table 7. This equates to 7.3 million tonnes of waste. It is in increase from 2014 where only 0.9% of waste were processed with energy recovery representing 1.9 million tonnes of waste. Three new facilities were commissioned between 2014 and 2016, however, the total number of incineration facilities with energy recovery increased by eight. It is likely that new facilities are designed for energy recovery, while older facilities without energy recovery are converting to enable energy recovery. It is foreseeable that the number of incineration facilities with energy recovery will increase over the next decade as older facilities are converted.

Table 7. Use and capacity of incineration facilities in the United Kingdom [55, 56]

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Incineration in the United Kingdom								
	Incineration only				Incineration with energy recovery			
Year	Mt	Capacity Mt/yr	% of all waste	Number of facilities	Mt	Capacity Mt/yr	% of all waste	Number of facilities
2012	5.9	8.4	3.1%	87	1.6	2.9	0.8%	27
2014	7.6	9.9	3.7%	83	1.9	4.9	0.9%	29
2016	5.7	8.5	2.7%	78	7.3	9.8	3.4%	37

The UK Strategy for Recourses and Waste reported that 3.4% renewable energy was generated from incineration of biodegradable waste in 2017 [57]. It is estimated that 2.3% of the UK's energy demand can be met through incineration with energy recovery should all the municipal solid waste that are currently sent to landfills be rerouted to incineration facilities [58]. Not only will this have a positive effect on the renewable energy generation in the UK, but also on greenhouse gas emissions generated from landfills. It is plausible that greenhouse gas emissions can be reduced by 2 million tonnes in this manner [106]. Legislation requires that biodegradable waste sent to landfills must be significantly reduced. This will see more municipal solid waste rerouted to incinerators providing an increase in feedstock and more opportunity for energy recovery from incineration. However, the current stance of the UK Government is that although incineration plays an important role in waste management the focus should be on prevention and recycling rather than landfills and incinerators. Taxation on the incineration of waste is likely to increase over the next few years which may reduce the economic benefit of this manner of waste management.

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3.2. Gasification

Gasification has been around for some time more than 80 years globally on a commercial scale in many industries and 35 years in the power generation. In partial oxidation process of organic substances, high temperatures of around 500-1800 ℃ are used. Partial oxidation is achieved by limiting the oxygen exposure at those temperatures so the gases produced known as 'syngas' do not combust but instead can be collected and stored for later use. These later uses include the chemical industry, as a fuel for the production of heat and or electricity or conversion into ethanol [59]. The syngas constitutes of H_2, CH_4, CO, CO_2, H_2O and N_2 with trace amounts of other hydrocarbons like propane and ethane. Predominantly air is supplied to the reaction site which in comparison to using pure oxygen results in a syngas of lower energy. Such that, in terms of heating value, pure oxygen gives 8.7 - 11.3 MJ/Nm^3 and air gives 4–7 MJ/Nm^3 [60]. There are 3 main types of gasifiers: fluidized bed, fixed bed and entrained flow which are capable of dealing with MSW, dried sewage sludge, some types of hazardous wastes and waste food among others. One of the key requirements for the feedstock is that it must be finely granulated, therefore MSW for instance requires pre-treatment. This is a clear negative side when compared to incineration, which comparatively has lower residue percentage of the feedstock. But there are positive comparisons such as lower volumes of gases produced mean smaller flue gas treatment systems can be used and smaller wastewater flows from syngas cleaning [7]. In addition, the overall thermal efficiency is more than 75% [61]. Furthermore, by the use of partial oxidisation, the amount of oxidized species such as SOx and NOx are reduced, which are replaced by H_2S, nitrogen and ammonia. Known to be better forms that can be scrubbed from the syngas than the oxidized versions prior to syngas utilization [62].

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In terms of gasification process a number of sub process take place. These constitute of a degree of pre-processing to remove inorganics such as metals and glass, which cannot be gasified, particle size reduction, drying (within the gasifier and in some cases prior to), oxidation and syngas collection. As can be seen the main waste product left over is slag (in high temperature gasifiers), this is similar to the bottom ash in the incineration process where metals and other valuable products can be recovered. Gasification of fossil feedstocks is an established process and is therefore rated at TRL 9. The use of biomass feedstock, such as municipal solid waste, is not readily applied in the UK. Although there are a number of plant in Norway, Germany, Finland, Italy and Sweden [63]. It was recently reported that operation had begun at UK's first municipal solid waste gasification plant located in Aldridge [64, 65]. To date the plant is operating on waste wood feedstock and the technology is not proven for municipal solid waste, although it is the intension to do so in the future. This is not the first gasification plant constructed in the UK for processing of biomass waste. Several such facilities have been built in the past and all have failed [66, 67]. One such example is the company Energos Ltd. that operated a gasification plant in the Isle of Wight since 2009 [68]. The plant made use of Refuse Derived Fuel (RDF) and was designed to provide 1.8 MWe power. The company had plans to build similar plants in Glasgow, Milton Keynes and Derby. However, the plant went into administration in 2016; the route cause was found to be a failure to deliver on gasification contracts. Another example is Ascot Environmental and its subsidiaries Planet Advantage and Scotgen that build a gasification plant in Dumfries in 2009. The plant was designed to deliver 6.2 MWe power from municipal solid waste and RDF feedstock. The company filed for administration in 2012 since the plant failed to produce energy during its three years of operation. The permit to operate that plant was revoked due to non-compliancy with the Scottish Environmental Protection Agency.

Fiscal incentives for the development of advanced conversion technologies, such a gasification of municipal waste, might receive more attention in the next decade [69]. The Engineering and Physical Sciences Research Council (EPSRC) does not have a specific research focus in this area but has supported gasification projects in the past [70]. Considering the past failures of the technology, it will be challenging to obtain the necessary funding to increase the TRL. Much depends on the operation and economic viability of the Aldridge plant and its ability to robustly process municipal solid waste on a large scale. The success of this plant will unlock the potential for gasification as biowaste processor. The failure however, along with the historical failure of similar plants, will be seen as conclusive proof that further development of this technology should be abandoned.

3.3. Pyrolysis

This process works on the thermal degradation similarly to gasification where partial oxidation is used to maintain the thermal conditions. Pyrolysis can also be achieved in complete absence of oxygen with an external heat source in inert conditions. Comparatively to gasification, pyrolysis works on lower temperatures of around 300 - 700 ℃ [71]. To date, although this technology is not new, it has not yet reached a widespread implementation. During the process, 3 products are made: solid coke, pyrolysis gas, pyrolysis liquid. The exact constitution and proportions of these products depends on the feedstock, reactor conditions, reactant residence time and pyrolysis method. The process can be optimized to maximize the formation of each product [72]. For example, in the case of fluidized bed reactors (fast pyrolysis), high temperature and high biomass residence time increases the production of gases; On the contrary, high temperature and low residence time however increases the formation of condensable liquid oils; then low temperature and high residence increases the production of solid coke. Typically, the pyrolysis gas, liquid and coke have calorific values of 5-16 MJ/kg, 22-25 MJ/kg and 33 MJ/kg respectively. The low heating values of the gases and liquids mean that upgrading is necessary to produce fossil fuel substitutes [73]. Pyrolysis can work on any hydrocarbon waste that can be cracked to release gasses, oils and char. For instance, FOG, MSW, food waste, manure and sewage sludge are all acceptable.

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One of the notable advantages of pyrolysis against other waste-to-energy processes is the higher energy density achievable of the products produced. But what some researchers don't mention is that these higher energy products were produced with external heat sources supplied to the reactor.

Furthermore, a degree of preparation is required to reduce feedstock particle size. Also, drying can be required depending on moisture content and the desired calorific value of the products. The inner stages are centralized around the reactions (thermal cracking) of the waste to release the pyrolysis products, which are then captured through condensing. The remaining coke is sometimes incinerated to rid of the organic matter remaining. Main pyrolysis reactor types include rotary kiln, fluidized bed, fixed bed, entrance flow, moving bed and more experimentally auger [74]. As hinted here, this process can be responsible of higher waste residue than gasification and incineration. This is mainly due to lower temperatures as a result of lower flue gas volumes after combustion of the products than incinerators [7].

As a general process, fast pyrolysis is currently deployed in operational environments with system completion and qualification. This places fast pyrolysis at TRL 8. Pyrolysis with upgrading, that increase the quality for the oil produced so that it can be used as transport fuel, is currently at TRL 5 [70]. There are 8 companies and 9 universities actively engaged in activities related to waste treatment through pyrolysis (Table 8). Activities are mostly aimed at waste-to-fuel applications instead of waste-to-energy. There are currently no large-scale facilities for pyrolysis in the UK.

Table 8. UK Companies and institutions involvement in pyrolysis

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Company/Institution	**Location**	**Feedstock**	**Conversion**	**Ref**
2G BioPOWER	Kent	Tyre	Recycling	[75]
Anergy Ltd	London	Biomass	Waste-to-Energy	[76]
Conversion and Resource Evaluation (CARE) Ltd	Down	Biomass	Waste-to-Fuel	[75]
Cynar Plc	London	Plastic	Waste-to-Fuel	[76]
Environmental Power International	Surrey	Various	Waste-to-Fuel	[76]
Future Blends Ltd	Oxfordshire	Biomass	Waste-to-Fuel	[75]
PYREG (UK)	Cambridge	Sewage Sludge	Phosphorous Recovery	[75]
Torftech Energy Ltd	Thatcham	Biomass	Waste-to-Energy Waste-to-Fuel	[75]
Aberystwyth University	Aberystwyth	Biomass	Waste-to-Fuel	[75]
Aston University	Birmingham	Biomass	Waste-to-Fuel	[77, 78]
Newcastle University	Newcastle	Biomass	Waste-to-Fuel	[75, 79]
University College London	London	Plastic	Waste-to-Fuel	[80, 81]
University of Cambridge	Cambridge	Various	Material Recovery Waste-to-Fuel	[75, 82]
University of Edinburgh	Edinburgh	Biomass	Waste-to-Fuel	[83, 84]
University of Leeds	Leeds	Biomass	Waste-to-Fuel	[85]
University of Sheffield	Sheffield	Biomass	Waste-to-Fuel	[86, 87]
University of York	York	Biomass	Waste-to-Fuel	[88]

The EPSRC are routinely funding research aimed the development of bioenergy. The bioenergy thematical area currently holds 14 research grants worth £12,511,100.00. There are a number of grants awarded that is specifically aimed at improving the pyrolysis process. These were all related to waste-to-fuel applications focusing on upgrading the quality of products to be used as marine and aviation

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fuel. Funding for waste-to-energy applications of pyrolysis remains uncommon. The financial and technical challenges will hamper the integration of pyrolysis as a process for waste management in the next decade. Pyrolysis as waste-to-energy mechanism is subjected to technical challenges [68]. The feedstock from municipal solid waste is inconsistent and will need significant preprocessing before it can be used. Blockages are often caused in pyrolysis plants due to tar deposition which lead to inefficiencies. Catalyst deactivation and choking can result in plant failure. These challenges are not negligible and has led to the limited application of this process worldwide.

3.4. Anaerobic digestion (AD)

As with incineration and gasification, Anaerobic Digestion (AD) is a well-established process within the waste to energy sector for the treatment of organic wastes. Dating back to the 1800s making it one of the oldest waste to energy processes. The concerns around the environment has increased its utilization when in 2007 England and Wales businesses were encouraged to use AD by the department for environment, food and rural affairs (DEFRA) to help meet energy targets set by the government [89]. Now, however, interest has dropped due to economic viability concerns. Investments and interest primarily come from businesses such as farms and not large waste industry companies, as the case studies included in the Royal Agricultural Society of England report show [90]. One of the main differences between AD and incineration/gasification is the predominantly large plant waste treatment centres, costing hundreds of millions. However even with the economic concerns, AD is still considered a key process for achieving a circular economy, increasing resource-efficiency and for the bioenergy-economy as a whole [91].

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The main feedstock for AD is manure and slurry, but it is not limited to these. Essentially, any organic matter can be fed into the digester such as WWS, FOG and food waste, as the process works on decomposition of organic matter. Microorganisms digest/eat the feedstock producing biogas, predominantly made up of methane (50-75%), with carbon dioxide along with traces of other gases making up the remaining percentage [92]. After the process, a solid mass known as digestate is left, a nutrients rich product that can be used as a fertilizer. As for the gasses produced, the high percentage of methane means it can either be upgraded to pure methane (main constitute of natural gas) or be combusted in a CHP plant. As Bywater [90] states ''The ratio of heat to power varies dependent on the scale and technology, but typically 35-40% is converted to electricity, 40-45% to heat and the balance lost as inefficiencies at various stages of the process, equating to over 2 kWh electricity and 2.5 kWh heat per cubic meter, at 60% methane''. There are two types of AD's: mesophilic and thermophilic, categorized according to their operation temperatures. The most common type (mesophilic) operate at temperatures between 20-45 ℃. Thermophilic digester operates at higher temperatures and most commonly used for sanitizing materials, so that they can be used for the benefit of agriculture.

Anaerobic digestors are widely used in the UK placing the technology at TRL 9. There are currently 661 digestors operational in the UK [93]. It supplies the national grid with biomethane (102 plants) and electricity (583 plants) and provide local heating (42 plants). The feedstock varies from agricultural waste (374 digestors), municipal/commercial waste (113 digestors), industrial waste (48 digestors), and sewage sludge (163 digestors). Between 2008 and 2017, 255 new anaerobic digestors were built in the UK with a total capacity of 193,354 kW [92].

The percentage of energy generated in the UK from bioenergy is steadily increasing (Table 9). In 2010 3.5% of energy generated were from biological sources. This has increased to 9.4% in 2016. Anaerobic digestors forms a component of bioenergy and is increasing as well. In 2010, 117 GWh electricity was generated with AD, accounting for 1% of energy generated with bioenergy. This increased to 2052 GWh in 2016, which is 7% of energy generated with bioenergy. AD is further discussed in section 4 where the environmental, economic, legislative and implementation is investigated.

Table 9. Electricity generated in the UK from bioenergy by year [94]

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Source	Units	2010	2011	2012	2013	2014	2015	2016
Landfill gas	GWh	5,217	5,318	5,208	5,175	5,033	4,872	4,703
Sewage sludge digestion	GWh	723	775	739	766	840	894	950
Energy from waste	GWh	1,529	1,504	1,773	1,648	1,900	2,585	2,741
Co-firing with fossil fuels	GWh	2,432	3,093	1,829	337	124	183	117
Animal Biomass	GWh	627	615	643	628	614	648	650
Anaerobic digestion	GWh	117	237	495	713	1,023	1,471	2,052
Plant Biomass	GWh	1,615	1,771	4,048	8,832	13,086	18,587	18,829
Total electricity generated from bioenergy	GWh	12,260	13,313	14,735	18,099	22,620	29,240	30,042
Total electricity generated from all sources	GWh	347,896	332,461	341,912	336,504	317,732	318,552	320,110

3.5. Hydrothermal Liquefaction (HTL)

This is the thermochemical conversion of biomass into oils referred to as 'biocrude oil' that can then be refined into petroleum derived fuels. The main advantage of this process is that water has a higher dissociation constant (and lower dielectric constant) at these operating conditions. The water is thereby less polar and helps to be a good solvent for hydrocarbon products and promote their reactions. As shown in Figure 3, the process is performed in a pressurized environment from 4 to 22 MPa, which avoids oxygen and heats to elevated temperatures between 250 - 374 ℃ [95]. These high pressures and temperatures help breakdown and reform biomass macromolecules into biocrude oil.

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As with anaerobic digestion, the process provides a means for processing wet biomass without drying that incineration, gasification and pyrolysis require. However, HTL is essentially pyrolysis in hot liquid water. As such, feedstock high in water content are suitable i.e. manure and sewage sludge. HTL biocrude oils contain a diverse range of chemical compounds, which present major challenges for downstream processes. This in some instances due to high heteroatom content in the biocrude oil can result in undesirable qualities, like acidity [96]. That said significant amounts of biocrude oil can be obtained from pig manure and digestate sludge. Vardon et al. [96] showed that at 300 ℃, 10-12 MPa and 30 min reaction time, pig manure and digestate sludge yielded 30% and 9.4% respectively with HHV's of 34.7 MJ/kg and 32 MJ/kg. With promising yields from biomasses, this process may become more widespread in the waste-to-energy sector in the future.

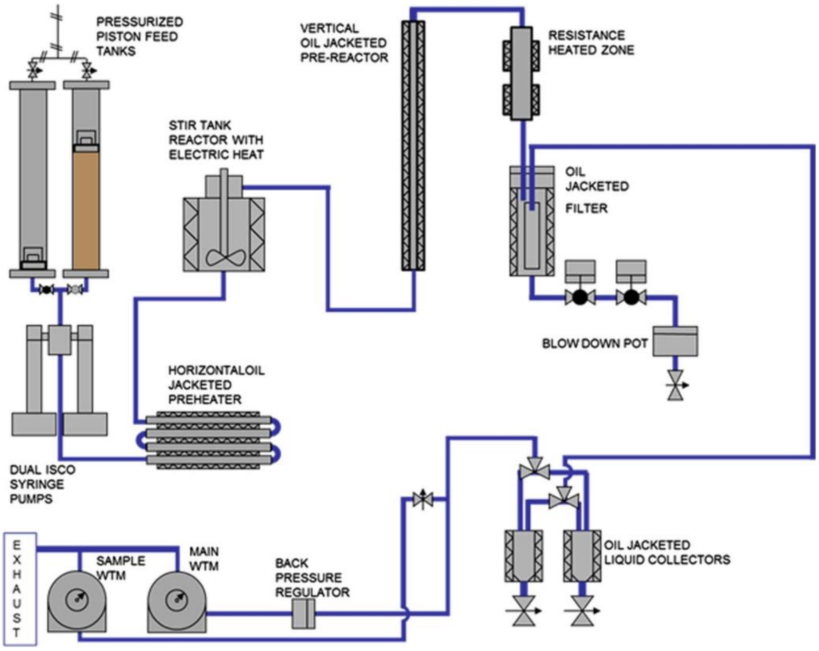

Figure 3. Diagram of HTL reactor system [95]

The current status of hydrothermal liquefaction in the UK is TRL4 since it has only been validated in the laboratory environment [70]. A recent review has indicated that the technology is immature with scaled testing at a limited number of UK universities [97]. The University of Leeds, Imperial College and Bath University are the only known institutions actively involved in experimental research in this area [98, 99, 100]. A recent review from the University of Surrey suggested the research focus for the process [101]. It highlighted the developments needed in the field to allow for both wet and dry biomass to be processed through this technique. Currently challenged associated with the process is catalyst performance, efficiency, product quality and handling of the high volumes of wastewater. Stirring large volumes of biomass slurry at high pressure is problematic and the solid content needs to be less than 35% to ensure pumpability. The process remains expensive due to the components necessary to operate in a corrosive environment at high pressures. The technology is expected to reach TRL 8 by 2030 [70].

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3.6. Summary of advantages and disadvantages of WtE processes

Looking at how prolific the processes are, HTL and AD lag behind incineration, gasification and pyrolysis in the UK, aligning with some of the issues discussed. Other process, such as fermentation, is used to some extent to produce bioethanol, but this is not so prevalent in waste feedstock streams. Incineration has been shown to be the most capable in feedstock admissions combined with the lowest end process waste percentages. However, this comes at the cost of lower efficiencies, high flue gas volumes and the loss of product extraction from the waste streams. The partial oxidations adopted in gasification and pyrolysis give advantages of lower flue gas volumes of which have lower percentage levels of oxidized species such as SO_X and NO_X, resulting in smaller flue gas treatment systems.

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The other main advantage is the product extraction possibilities. Notably pyrolysis process results in products of higher energy density. Although not discussed, plasma pyrolysis and plasma gasification among others are some of the technological advances of these processes, essentially working at higher temperatures to create more reactions and result in less end process. AD is shown to be different from the other processes, attaining products without the need of high temperatures and complex systems. But AD is limited to predominately manure feedstocks and economic uncertainties through lowering levels of government schemes and grants. This is alarming, considering a degree of pollution raw manure is responsible for. HTL offers a pathway to obtaining bio crude oil which can be upgraded and refined to match petroleum-based fuels from waste streams, unlike other processes that use more valuable resources, such as rapeseed biodiesel, for instance.

One thing that has been made clear across literature of WtE processes is that although some of the processes have the ability to deal with a wide variety of wastes, the facilities are usually specifically designed to suit one particular waste stream. For example, in 2009 the chimney of ConTerm pyrolysis plant in Hamm Germany collapsed. The accident was the result of an insulation problem which lead to very high temperatures and softening of the steel structure. It was later found that inadequate sorting of the waste stream was a key contributor, as the feed characteristics exceeded the process design resulting in excessive temperatures past tolerable limits [7].

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The utilisation of waste streams for energy and products has proven to be well documented, with landfills now considered as temporary storage. Waste FOG’s and food can be fully utilized for WtE processes, same goes for WWS. Despite the widespread implementation/capture of these wastes in the UK, it still requires a degree of work in achieving a circular economy as the government plans.

4. Discussion on the Effects of Manure and Barriers to Processing

When looking at preventative environmental emissions, manure as a feedstock remains largely untouched. As a result, high concentrations of NO_X, ammonia and methane, which are retained in the manure are emitted into the environment. A complete contrast is shown to strict legislation placed on internal combustion engines for NO_X emissions, which in fact, account for far less of the anthropogenic emissions than manure. These and other wastes discussed in the previous section should be the subject to a higher attention even if they are responsible for a lower fraction of the emissions of manure. Therefore, this section will cover the issues of manure and anaerobic digestion related to the environment, economics, legislature, and implementation. It will discuss the severity that untreated manure can pose in the UK through emissions of nitrous oxides, methane, and ammonia. Amount of emissions produced by manure can be mitigated through WtE processing by avoiding the barriers preventing the implementation of this as a whole, and also bringing most of manure generated in the UK under pollution control.

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4.1. Environmental effect of emmisions from manure

4.1.1. Ammonia

Overall, the agricultural sector accounts for 88% of all NH_3 emissions in the UK and is estimated at 94% in the EU [101, 102]. The lack of manure and sludge treatment in the UK results in the livestock industry accounting for 66% of all ammonia emissions, as shown in Figure 4 (b) (not including grazing/outdoors), according to the Department for Environment Food and Rural Affairs (DEFRA) [102]. The figure related to manure and slurry production is not taking into account cattle graze on open fields for at least half a year, not counting some unavoidable proportion of ammonia (NH_3) emitted into the atmosphere. Report on NH_3 emissions produced by agriculture sector was prepared by DEFRA. Figure 4 (a) shows the proportion of ammonia emissions per livestock.

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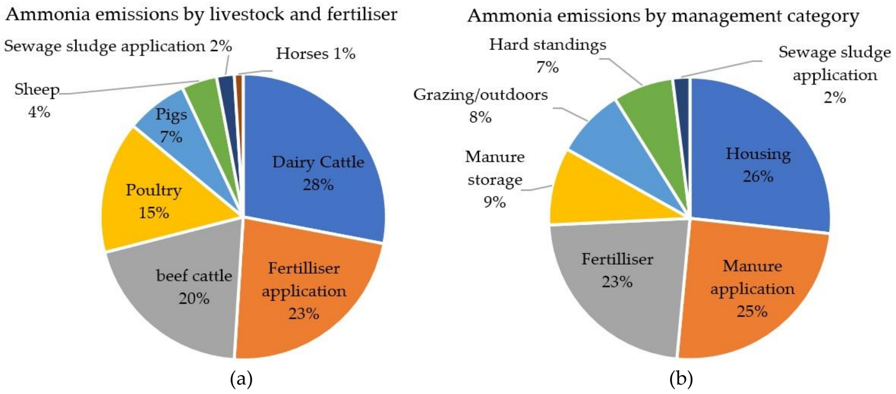

Figure 4. Ammonia emissions within agriculture by (a) livestock and fertilizer category and (b) by agricultural management category [102]

An estimation from Figure 4 can be made on the true amount of NH_3 emissions, the direct result of manure formation and slurry at around 40 % (Manure storage 9% + Grazing 8% + Hard standings 7% + Sewage sludge 2%) of 66% of all ammonia emissions subject to unavoidable losses through animal grazing and hard standings. Hard standings are defined as unroofed paved or concrete areas. Examples include areas outside the milking parlor, where dairy cows congregate prior to milking. Meaning that up to 40% of NH_3 has the potential to be avoided with widespread waste to energy processes applied. This 40% in 2019 amounts to 86.2 kT of NH_3 emitted every year [103]. As NH_3 is a soluble alkaline gas with a high reactivity, the effects to the environment are numerous. In terms of the atmosphere, it reacts with acid pollutants such as the products of SO_2 and NOx emissions to produce fine ammonium NH_4+. Both forms have a lifetime of 10-100 years which lessen the overall effects atmospherically but creates localized affection zones with high concentrations of NH_3 and ammonium fallout [104]. The effects of ammonia vary as it is a commonly found naturally. One of the most notable aspects is the unpleasant odour, which even at low concentrations due to the pungency is still detectable. In the atmosphere, it can be an irritant to the eyes throat and lungs in high concentrations, the ammonium can penetrate deep into the lungs with links to respiratory problems and diseases due to the fine particle size [105].

For vegetation, ammonia is on the most part beneficial as a source of nitrogen essential for the formation of amino acids. When in the form of ammonium and is deposited onto soil it is converted by bacteria into nitrates which are then absorbed by roots increasing growing rates of nitrogen loving plants. But this can lead to imbalances affecting biodiversity, where nitrogen loving plants take over smothering out other species less effective in nitrogen take up. NH_3 pollution also effects species through soil acidification, damage to leaves through a burning effect reducing the resistance to frost, pathogens and drought. These negative effects in a report conducted by RAND [106] say that by 2020 the negative impacts could be equivalent to the cost of more than £700,000,000 per year.

The effects of NH_3 in water sources is notably more severe, with links to eutrophication and acidification, where in concentrations ranging from 0.53 to 22.8 mg/L it becomes toxic to freshwater organisms. The toxic effects differ depending on species but generally fish may suffer loss of equilibrium, hyper excitability, increased oxygen uptake and increased heartbeat rate. In extreme levels NH_3 can cause fish to suffer convulsions, coma and death. Even at levels below 0.1 mg/litre fish can experience irritation, gill damage, reduction in hatching and growth rates [107]. Fish and aquatic life can also be indirectly affected through eutrophication creating algal blooms reducing the amount dissolved oxygen.

4.1.2. Nitrous Oxides (NO_x)

This is another notable pollutant given off by manure, known for its high GWP of 298 times that of carbon dioxide. The lifetime is around 110 years in the atmosphere where the process that removes NO_x from the atmosphere contributes to depletion of the ozone layer [108]. Aside from methane and ammonia, NO_x is the 3rd biggest contributor in emissions from agriculture. The degree of NO_x produced from manure is dependent on the amount of aeration where the greater availability to oxygen leads to more NO_x formation. Looking back at the waste to energy processes, anaerobic digestion offers the most suitable option in limiting NO_x formation. The amount of NO_x emitted as the direct result of manure is unknown, however the overall NO_x emissions from agriculture are known to be 27 kT in 2017 [109]. This amounts to 3% of the total NO_x emissions in the UK, with transport contributing the most, 34%. Contradictory to this data, the national statistics for the UK in 2017 showed that in fact agriculture is responsible for 70% of NO_x emissions, amounting to 14.3 Mt CO_2e [110].. As both are from reputable governmental sources, this serves as an example of the degree of uncertainty these estimates are subject to. Nevertheless, more trust will be placed on the higher figures when looking at another report stating it to be 65% [111]. Similarly, to the NH_3 emissions, the amount emitted as the result of manure can be expected to be considerably less. 28% is a reasonable estimation if manure amounts to 40% of agriculture's overall impact.

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4.1.3. Methane

As with nitrous oxides, methane presents a significant contribution to greenhouse gases with a GWP 25 times that of CO_2 and a lifetime in the atmosphere of around 10 years, where other chemicals in the air are responsible for its removal. The main source of methane is from the natural decomposition of organic matter in anaerobic conditions. As manure and slurry present large quantities of organic matter they contribute significantly to the agricultural sectors total emissions 51% of the UK's anthropogenic methane emissions in 2015 [112] and 50% in 2017 [110]. Figure 5 shows this in comparison to other sectors highlighting again that agriculture is the biggest contributor. Unlike NH_3 and NO_x emission where artificial fertilizer contributes heavily, methane is almost exclusively from manure, slurry and the animals' digestive systems. As the animals are known to be high contributors a ballpark estimation would be that 45% of methane emissions within agriculture are the direct result of manure and slurry. This in wider terms translates to 22.5% of total methane emissions in the UK.

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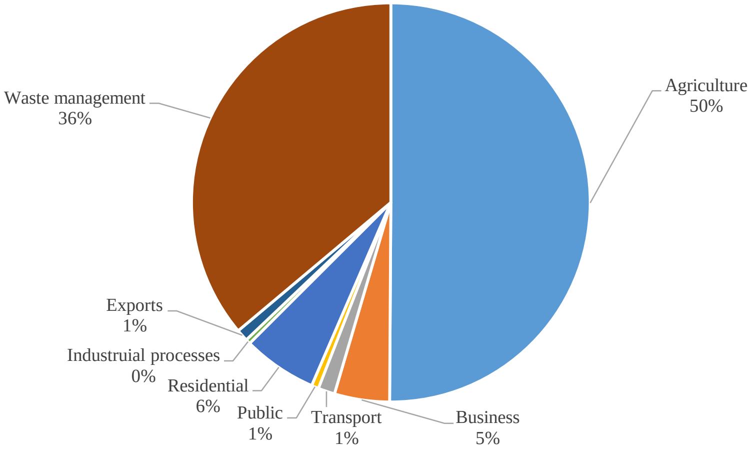

Figure 5. Methane emissions by sector in 2017 [110]

Methane can present an explosion risk at 5-15% content in the air [113]. There are numerous documented incidents where methane has been the result of gas fires and explosions in agriculture. For example, under certain conditions in which animals are fed a particular diet, this can result in the formation of bubbles containing methane in the slurry. The bubbles have been known to form a foam above the slurry which is susceptible to combustion [114].

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4.1.4. Anaerobic digestion of manure as mitigation strategy for harmful emissions

The waste to energy conversion of manure to electricity, heat, fuel or grid gas is a four-stage process, as shown in Figure 6, consisting of hydrolysis, acidogenesis, acetogenesis and methanogenesis [115]. Manure feedstock is complex organic matter that consist of carbohydrates, proteins and fats. Through hydrolysis this is converted to soluble organic molecules such as sugars, amino acids and fatty acids. Acidogenesis or these components lead to the formation of volatile fatty acids, acetic acids, hydrogen and carbon dioxide. The volatile fatty acids is converted to acetic acids, hydrogen and carbon dioxide through acetogenesis. The last stage of the process is methanogenesis that forms biogas which can be converted into biomethane. Biogas is used at fuel in electricity and heating applications, while biomethane can be directed pumped into the national grid. Each stage the process is reliant on a number of microorganisms to participate in the reactions. Since this reaction occurs in an oxygen lean environment, there are less oxygen molecule to bind with the nitrogen molecules and form NOx.

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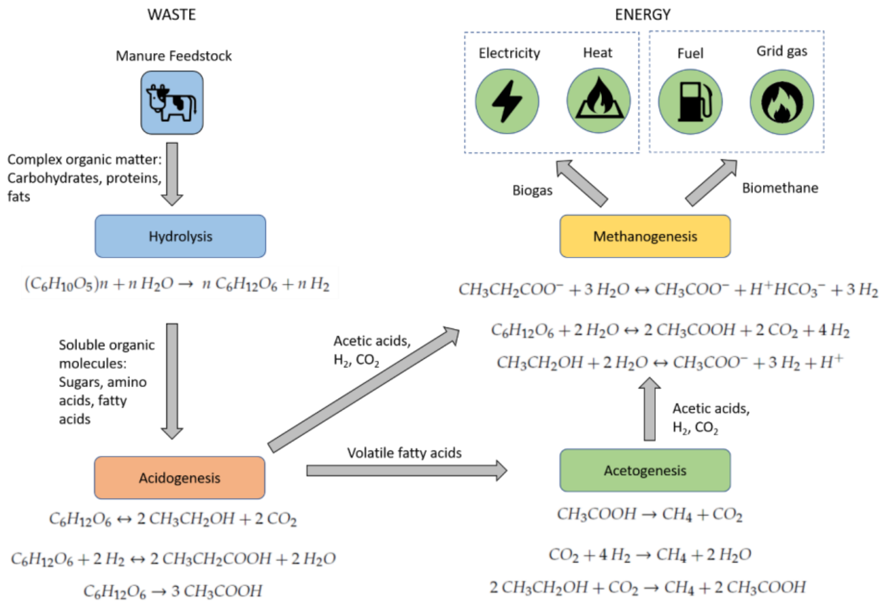

Figure 6. Waste-to Energy-process using manure as waste feedstock

As highlighted, NOx formation is related to the degree of oxygen present when organic matter is decomposing, but when in an anaerobic environment, methane emissions increase. In the process of anaerobic digestion, this is ideal where the methane can be captured and used. In work produced by Sommer et al. [116], algorithms were developed for calculating methane and NOx emissions from manure management [116], in which, the degree of emission reduction through anaerobic digestion was calculated. The model predicted 90% reduction of methane from outside stores with digested

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slurry. The digested slurry/muck is said to have a reduction of more than 50% of NO_X emissions after the application of the digested slurry onto agricultural land vs that of untreated slurry. No estimations were made regarding the effect on NH_3 production, where this is considered an anaerobic digestion inhibitor, through the change in pH. High toxicity levels also destroy microbes that produce methane [117].

For reduction in NH_3 emissions, it is clear that anaerobic digestion is not best suited to this. The addition of magnesium ammonium phosphate otherwise known as struvite is said to reduce NH_3 levels in a digester. Where struvite is a valuable plant nutrient source that slowly releases nitrogen and phosphorus overtime, it also known for its low solubility in water. Uludag-Demirer et al. [118] in an experiment added a set amount of struvite to a digester, resulting in 11% NH_3 reduction. Other work in this area also highlights the role pH plays, highlighting reactor conditions having a significant impact. Apart from optimizing reactor conditions and introducing additives, further processing would be the next cause of action. The anammox process is one such process aimed at post digested effluent. It is considered an efficient biological method for nitrogen removal through ammonium oxidization to nitrogen gas in anaerobic environment. Molinuevo's experiments [119] found that up to 92% of ammonium could be removed this way. As it can be quite costly to remove the NH_3, others look towards how the manure is applied to soil and if emission mitigation can be achieved there. Some of the main techniques from this aim towards limiting the mixing the slurry and muck have with the atmosphere through trail hoses and direct injection. The trail hoses limit the surface area that the muck and slurry is applied to. From Sommer and Hutchings [120], this is said to reduce the amount of emitted ammonia by 40%. For injection, this figure is said to be even higher at 60% when in combination of harrowing prior to the application.

4.2. Economical aspects of anaerobic digestion

4.2.1. Current Incentives

As mentioned in the AD description, incentives have been on the decline at current, it can be assumed that almost all grants have been withdrawn by the government. Similarly, the tariffs in recent years have been reduced from 15.15 pence/kWh in 2010 to 4.50 pence/kWh in Jan 2019 for biodigester units less than 500 kW [121]. The gradual change in tariff rates for all sizes of AD is shown in Figure 7, offering a depiction of the decrease in the amount of government funds made available per year. The curves show the tariffs in pence/kWh for three bands of installed capacity: 0-250 kW, 250-500 kW and 500-5000 kW. Some studies suggest that such change in tariff rates is too high for average size of UK farms and that lower boundaries should be introduced. Even incorporating the sale price tariffs, the cost viability particularly for small scale farm systems comes into question. This can be linked with the step decline seen in the number of AD plants commissioned each year. Where from the peak of 79 new plants commissioned in 2014 a fraction of that number is now commissioned which was only 6 in 2017 [122]. This is shown in a graph taken from Savills summary [123] on AD growth and performance depicted by Figure 8. A clear link can be seen between the drops in tariff rates from 2014 to 2015 shown in Figure 7 to the fall in plants commissioned per year shown in Figure 8.

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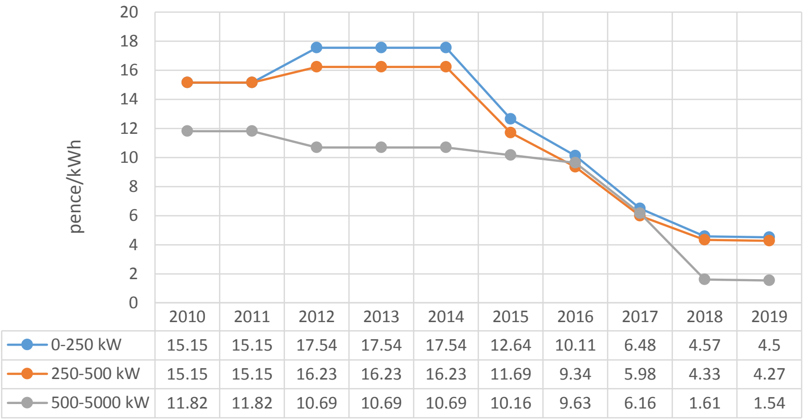

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
0-250 kW	15.15	15.15	17.54	17.54	17.54	12.64	10.11	6.48	4.57	4.5
250-500 kW	15.15	15.15	16.23	16.23	16.23	11.69	9.34	5.98	4.33	4.27
500-5000 kW	11.82	11.82	10.69	10.69	10.69	10.16	9.63	6.16	1.61	1.54

Figure 7. Change in generation tariff rate for anaerobic digestion [121]

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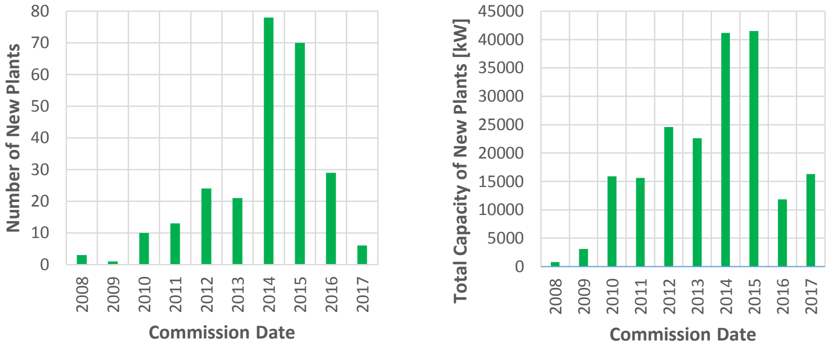

(a)

(b)

Figure 8. (a) n~~N~~umber of AD plants commissioned from 2008 to 2017 in UK~~ (a)~~ and (b) the total capacity of these plants in kW~~ (b)~~ [123]

The numbers are very low considering the number of farms in the UK and goals set out by the DEFRA and National Farmers Union (NFU) aiming for 1000 on-farm AD plants by 2020 [124]. The actual number by 2020 will be considerably less highlighting the lag that this industry has to overcome if it were to pose a significant reduction in GHG emissions and averted emissions through methane capture pathways.

4.2.2. Capital Grants and Finance

The lag on the farm scale can be mostly put down to the capital costs required for installation. Almost all AD plants surveyed has some form of capital subsidy at 93% according to Bywater [90]. This is in part due to the financial status of smaller farms which can struggle to break even relaying

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on receiving farm payments from the government every year, making it unlikely that the capital would be available for such an investment. This lack of capital changes the use pathway of the methane gas, where expensive onsite gas cleaning and combustion in gas engines is not an option. Thus, the gas produced is merely used in boilers to heat farmhouses and to use for hot water, losing the potential for self-electricity generation and associated benefits. It is also worth noting that the tariff system changes onto the renewable heat incentive (RHI) as a result. A system not designed for this sector is providing yet a smaller insignificant income. Currently for small biogas combustion of which this pathway would fall under, the rate stands at 4.74 pence/kWh as shown in Table 10, further lowering the economic prospects for farm AD.

Table 10. Tariff rates for RHI (small biogas combustion) [125]

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Eligible Technology	Eligible Sizes	Accreditation Date	Tariff Rate 2019/20 (pence/kWh)
Small Biogas Combustion	Less than 200 kWth	Before 1 April 2016	8.44
		Between 1 April and 30 June 2016	7.41
		Between 1 July and 30 September 2016	6.30
		Between 1 October and 31 December 2016	4.74
		Between 1 January and 31 March 2017	3.54
		Between 1 April and 30 June 2017	3.37
		Between 1 July 2017 and 21 May 2018	3.03
		On or after 22 May 2018	4.74

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4.2.3. Supply of slurry and muck

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There is a high volume of slurry and muck produced on farms, where for instance, a pig unit near York with around 5000 pigs produces 20m^3 of slurry a day and over 1000 tonnes of muck each year. More can be said of the future with farm operations switching to fewer much larger operations, as small holdings with less than a couple hundred acers struggle financially with expensive farm machinery required to operate and the lack of land and livestock to spread overheads over. It is said that in the UK, 4.5 times as much derived organic matter is produced from farm operations (including slurry and muck) as from food, 90 million tonnes compared to 20 million tonnes [90]. Thus, the supply is not an issue.

4.3. Legislation controlling implementation of anaerobic digestion plants

4.3.1. Environmental Permitting

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This is the primary means of regulating and minimizing the impact business activities have towards all environment aspects for England and Wales, such as to the air, water, land and considering factors like noise and safety. For AD plants to operate and spread digestate, a permit must be obtained. This involves completing a technical application form, demonstrating competency and willingness to abiding by the conditions of the proposed permit. Currently this can be achieved through Charted Institution of Wastes Management / Waste Management Industry Training and Advisory Board (CIWM/WAMITAB) scheme or Environmental Services Association / Energy and Utility (ESA/EU) sector skills. Setting out 3 different types of permits as shown in Table 11.

Table 11. Anaerobic digestion permits

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Type	Description	Conditions
Exemption	For small scale plants which aren't waste facilities	• Must provide technical information to the environment agency and register • No charges • Only for agricultural businesses and burning of resultant biogas at the site. • 1,250 m^3 limit for the total amount of untreated and treated waste on site at any time • 0.4 MW limit for the thermal generating capacity of the plant • Minimum 28 days residence time of the waste [126]
Standard	For plants which can operate within a set of standardised rules and conditions.	• AD processing facility including the use of the biogas • 100 t processing limit per day • Combustion of biogas can be in gas engines, boilers, turbines, fuel cells or upgrading to bio methane [127]
Bespoke	For plants that cannot adhere to all pre-defined rules or conditions	The conditions vary considerably where both stationary and mobile AD plants are categorised for in this type. However, the flexibility of this type comes at more cost and time. Details can be found on the government website [128].

4.3.2. Permits for Spreading Digestate

As with exceptions to environmental permitting, digestate that is solely from agricultural waste streams is exempted from disposal charges provided that a number of conditions are met. These are:

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- Only can be spread on agricultural land
- 50 t per hectare spreading limit
- 200 t storage limit at any one time
- Digestate must be from waste streams that improve or maintain the physical, chemical and biological properties of the soil to grow crops [129]

Note that material that has reached PAS 110 and Quality Protocol standards is no longer regarded as a waste. As such, the restrictions above no longer apply.

To spread waste material which does not meet the publicly available specification (PAS) 110 for agricultural and non-agricultural land for business or environmental enrichment, a permit is required. That is if the spreading activities to agricultural land exceed the exception conditions. Generally, a standard rule permit is given with the conditions and charges depicted in the government publication "SR2010 No.4: Mobile plant for land spreading" which specifies:

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- A 250 t per hectare spreading limit
- 3,000 t limit for the amount of waste material on site at any time
- 12-month storage limit for the material
- For every spreading application of material to the land a charge must be payed depending on material type and the risk it poses, ranging from low, medium and high

High risk (Category 2) animal by-products (ABPs) cannot be used as feedstock in AD plants, unless they have been treated to a 133°C/3 bar/20-minute EU pressure-rendering standards [130]. Contrary to this manure is classified as a category 2 ABP, however, manure can be used without processing as raw material in an AD plant. But when mixed with ABPs such as catering waste the mixture must be rendered to the heat and pressure regulations prior to anaerobic digestion.

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4.3.3. Planning Permission

Potential issues surrounding planning of AD plants revolve around 5 main concerns as highlighted from the governments planning policy statements and supplementary planning guidance [131]. These are:

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Site Selection. The AD reactor tank can sometimes be quite large presenting a significant change to a landscape, where tanks can reach as high as 15 m. However small on farm digesters can sometimes be accommodated within the farmyard and buildings concealing it to an extent. Where this may not be possible, in the interest of reducing tank visibility, it can be somewhat burried in the ground reducing the visual impact. The burial also offers heat insulation benefits. Centralised AD plants have issue of the transport of feedstock involved, affecting chances of approval, giving on-farm plants the advantage.

Feed Stocks and Product Storage. Planning permission may be given only for specific feedstock, adding to or changing the feedstock is not allowed without further planning consent. This ties in with the exception permit given to farms that by adding other feed stocks it can lead to the exception being revoked. The storage of slurry and muck used in on-farm AD plants is covered by the water resources (control of pollution) (silage, slurry and agricultural fuel oil) England regulations and the nitrates directive (91 / 676 /EEC). Specifying the minimum standards for construction related to the design and operation of any farm slurry storage system.

Odour. AD by its nature of breaking down organic matter is an odorous process, this is of concern. Where predicted odour effects and proposed mitigating measures should be reviewed. If a location is considered to be sensitive to odours, information on the control measures should be provided from the developer to ensure that all sources are accounted for. Farms are already known for to be odorous and thus odour concerns are lessened to those of centralized facilities.

Emissions to Ground and Water Courses. As has been made clear in previous section, the runoff from raw agricultural wastes such as manure and slurry can contribute to serious farm pollution incidents. Therefore, the AD of farm waste should be conducted in a manor to reduce the likelihood and ability of the material to pollute water sources. In many application cases, the requirement of a bound wall is put forward by the planning authorities to prevent effluent spillage in the event of a leak. As for ground water leaking, the surround surface of a supposed plant is usually required to be concreted and run off prevented from reaching normal drains. Delays in the planning process can be the result of concerns in regard to designs inadequacies.

Emissions to Air. The production of biogas from AD and its uses contributes to a number of emissions to the atmosphere, manly from engine exhausts, gas vents and flare stacks. The emissions can however be considered insignificant provided the equipment meets design specifications and is routinely serviced. For larger on-farm and centralised AD plants integrated pollution control measures are required to control the emissions to meet regulations.

4.4. Implementation of anaerobic digestion to farms

4.4.1. Slurry and Manure as a Feedstock

Without adding other feedstock, the AD of slurry and manure has been proven to be uneconomical for both on farm and centralized plants due to the low gas yields, high capital cost and absence of gate fee. The legislation also plays a large role here in the restrictions placed on the exception type permit for farm-based plants. Other wastes such as those from grain processing can be added to increase gas yield without increasing the potential environment effects. In surveys conducted in 2017, it was reported that there were 401 AD plants in the UK, if those for treating sewage sludge are ignored, with more than half at 221 utilizing slurry and manure as feedstock. However, those dedicated to only slurry and manure are uncommon making up just 6% equating to 24 plants, with the capacity of processing 165,000 tonnes per year [132].

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4.4.2. Grid Connection Issues

For widespread implementation of AD to farms, significant issues can be expected in connecting to the grid in part due to the low load electricity lines supplying many farms and the power of transformer. If the national grid deems the transformer inadequate, this can make the implementation of an AD plant to produce electricity not economically viable. Because it is presumed that small AD plants are unlikely to produce significant extra electricity that can be sold to the grid.

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4.4.3. Lack of Land

From the regulations on digestate spreading where 50 tonnes per hectare is the spreading limit, large livestock farms particularly those where the animals are kept indoors all year round and have little in terms of land can be a significant issue. On the contrary these farms must find ways to get rid of slurry and muck like the straw-muck exchange highlighted in the feedstock preliminary section. And if this were to be replaced by digestate the application rates are the same. If PAS 110 and Quality Protocol standards are achievable, converting slurry and manure to digestate would be very advantageous for surpassing the application limits.

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4.4.4. Technology

If widespread implementation were possible this could see a significant contribution to the UK's energy demands if the majority of manure and slurry were to be processed. This amounts to 90-100 million tonnes of agricultural by-products such as manure and slurry available each year in the UK. This is based on a 20 m^3/t (8% dry matter) average gas yield of slurry, that 1.7 kWh of electricity is produced per $1m^3$ of gas due to conversion losses and if 50% of the available manure/slurry can be processed, 1.615 TWh worth of electricity could be produced. A reasonable estimation which could provide 0.45% of the UK's annual demand, based on 2018 at 352.064 TWh [133]. A low percentage, but after considerations of the useful heat that can be harvested alongside the emission mitigations, it becomes more considerable. But the low electricity generation is a limiting factor in the technology potential.

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4.4.5. Operation

The success of an on-farm AD plant, no matter how good the design nor technology, is inevitably comes down to operator skills, frequent monitoring and feeding the digester. On many farms, the muck and slurry are required to be mixed into the digester at a certain ratio for instance. Adding to this AD's can be plagued by a number of problems namely:

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- Frothing
- Acidification
- Increasing viscosity
- Increasing volatile fatty acids (VFA) and total inorganic carbon (TIC) value
- Poor methane yield

These problems, if not corrected and kept on top off, can lead to poor biogas yield. Frothing alone can reduce biogas yield by up to 20% [134], with the cause linked to the constitution of the digestant and mixing routines within the reactor tank. These problems make time allocation and training a must for the farmer/operator. As such, a best practice guide should be made available if not already on the operation of AD plants specific to slurry and manure.

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4.4.6. Bespoke cases

One size does not fit all in the case of widespread farm implementation, every farm is individual and presents its own challenges. The differences from farm to farm can be enormous from the amount of slurry and muck produced, to the characteristics of the feedstock and the planning complications. At a government level to seek to drastically increase the number of on-farm AD plants, this would prove complex as what may be beneficial to one may be inadequate to another.

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Here, we provide two cases of commissioning of anaerobic digesters, which use manure as a feedstock. The first case is the Copys Green Farm located in Wighton, Wells-next-the-Sea in the eastern part of the UK, as shown in Table 12. The farm is very much sustainability driven and owners won a number of awards for doing so, namely the Farmers' Weekly green energy farmer of the year 2010. Note that £100,000 grant from bioenergy was turned down due to stopping double Renewable Obligation Certificate / Feed-in Tariff (ROCs/FIT) from being revived. Payback period was estimated at 8 years with a £83,000/year running cost most of which was the high energy feedstock. The biogas was produced at the rate of 70 m^3/hr burned to generate 131 KVA for grid export. In the planning and development stage the biggest barriers to on-farm AD is described as administrative. This includes the environment agency and OFGEM paperwork, where the owner feels the paperwork is disproportionate to the risk.

Table 12. Summarised data of Copys Green Farm [90]

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Digester Size	870 m^3 (mid to large size)
Digester Type	Mesophilic, insulated, steel glass coasted tank with fixed roof
Gas Use	140 kW CHP, Feed in tariffs, extra heat used in grain drying, cheese making, dairy hot water and heating the farmhouse.
Commissioned	2009
Feedstock (tonnes per year)	Slurry from 100 dairy cows estimated at 2,500T/yr, Maize Silage or fodder beet estimated at 2,500T/yr, Whey from cheese making supposed feed stock to be incorporated but not yet would be around 210T/yr
Farm Size	230ha, arable and dairy, all in NVZ (Nitrate Vulnerable Zone)
Capital cost	Estimated to be £750,000, self-financed, with £100,000 capital grant turned down.
Issues	Unreliability of CHP. Tech provider issues (takeover midway through project)
Barriers to AD	Administrative: EA and OFGEM paperwork
Advantages	Recycling and improved utilisation of crop nutrients. Reducing risks the manures pose to NVZ area as digestate

The second case is a Woodhead farm located near Annan in Dumfries and Galloway in the western part of the UK, as shown in Table 13. A SlurryGen-50 digester was installed by Advanced Anaerobics Ltd. to help reduce electric bill and generate income [135]. 500 kWh is used each day of the total 1,200 kWh produced with the balance exported to the grid. Owners applied for the feed in tariff in 2014 securing 12.46 pence/kWh. The excess heat is planned to be used on farm and generate additional income through RHI scheme. With these tariffs and savings to the electricity bill, payback period is estimated 60 months (5 years). It is said that for each ton of dry organic matter in slurry can produce 300-400 m^3 of biogas. Operating cost is highlighted as an issue in this case study, because for example the CHP generator requires routine maintenance and periodic engine rebuilds. Over a 20-year lifetime, the operating costs of the plant as a whole will exceed the initial capital cost.

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The Farmers' Weekly points out that in 2015 only 18 slurry AD plants were running in the UK. There were however 20-30 units at the planning stage. More widely 280 on-farm plants have been encouraged with RHI and FIT's.

Table 13. Summarised data of Woodhead farm [135]

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Digester Size	Small
Digester Type	Mesophilic, insulated, steel glass coasted tank with fixed roof

Gas Use	50 kW CHP, some used on farm, rest exported to grid through feed-in tariff. Surplus heat planned to be used on farm under RHI
Commissioned	2015
Feedstock (tonnes per year)	Slurry from 320 dairy cows estimated at 24 T/day
Farm Size	n/a
Capital cost	Estimated to be £400,000 (self-financed)
Issues	Operating cost due to small plant
Barriers to AD	Administrative: EA and OFGEM paperwork
Advantages	Smaller size, simplified planning and permits, as does not need crop or other material brought in, there is no requirement to qualify as consented waste management site and lower capital cost.

4.5. Summary of manure and AD implementation

Manure and slurry present significant anthropogenic emissions of NH_3, NO_X and methane in the UK at 40%, 28% and 22.5% respectively. This requires that anaerobic digestion mitigations of 90% in methane from stores and 50% in NO_X emission after the application to land can be achieved. However, AD has poor NH_3 reduction capabilities, requiring extra processing. Although a more effective migration pathway may be to change how muck and slurry are applied to land, a reduction of up to 40% is achievable by minimizing aeration.

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Sharp drops in tariff rates, high capital requirements and lack of grants make the economic side of AD an issue. On-farm AD has been named numerously as the most suitable type for manure but the least viable. Therefore, reforms to the incentives are a must if the number of AD plants are to increase in the UK, especially on-farm types which rely on grants. As the current tariff banding system is unsuitable for on-farm AD, implementing higher paying bands would be advised. A gate fee for processing, which includes the cost of opening, maintaining and eventually closing the site and also may include taxes applicable in a region, would also be advised to reduce dependence on biogas yield and temptations of using high energy crops.

Legislation and planning play a key role in the establishment of farm digesters with exception permits designed for this scenario, but for an exception to be grated strict rules apply. For more normal or unique operations, two other permit types (a standard rule permit SR2010 and a planning permit) can be granted at a cost and more time. The quality of the digestate is key in what can be done with it and how much can be applied to agricultural land. For use on non-agricultural land digestate incurres charges, limitations of quality and permitting (if still a waste). Manure is also found to be categorized as a high-risk waste which presents pressure and heat rendering incursions. These can however be ignored provided it is not mixed with other animal by-products. Overall, the legislation can be said to be well founded and necessary. Planning permission for many is where issues arise in legislation delaying a project or preventing its construction. The case studies show legislation is a barrier to AD. But as the planning difficulties are routed in reducing the risk an AD plant poses to the surrounding environment, no changes are envisaged as to ease the implementation of wide spread AD plants, with the environment as one of the primary focuses of this paper.

A significant amount of electricity could be produced, at 1.615 TWh equivalent to 0.45% of total UK's annual demand. Potential grid connection issues can limit this but for small on-farm plants encouraged in this report it can be said to be minimal, with the majority of the useful energy used onsite. Furthermore, the bespoke requirements for on-farm AD are known to present difficulties for the widespread implementation. Finally, as stated, inevitably the success of an AD plant comes down to operation. Improper monitoring and lack of know-how can lead to poor gas yields through problems common to digesters. Therefore, training and courses on operation are a must not just to prove competency for attaining permits but also for good operating practice.

5. Conclusions

Waste-to-energy sector is well developed with a number of processes capable of dealing with a variety of waste streams for energy and product extraction, improving sustainability and waste management, critically displacing fossil fuels and transferring towards a circular economy. However, challenges remain in the effective implementation of these processes in the UK. From the existing body of studies, it is clear that no 'quick fix solution' will guarantee energy sector decarbonisation. Conventional bioenergy's capacity to produce significant GHG reductions is being constantly debated. Sustainable residues and waste from biomass may and should definitely be part of this solution. This review has focused on certain waste streams such as biomass residue and agricultural waste, landfill waste, food waste, fats-oils-grease, wastewater sludge and manure, because they are considered potentially sustainable feedstocks. With a broad variety of current applications for several of these feedstocks, it will require strong environmental protections to avoid harmful environmental and social outcomes. Although the amount of such waste materials will be raised, it will decrease for certain wastes. Given the importance of several other applications, only a portion of the future flow of such resources can be devoted to the development of bioenergy. Of this among other purposes, there is substantial confusion regarding the exact quantities among energy values of the feedstocks that could be used sustainably of bioenergy development in the UK and further research on this is desperately required, taking into account economic forces, competitive applications, environmental imperatives and other considerations.

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90 million tonnes of manure and slurry in the UK remain largely untapped, presenting the biggest contributions to ammonia, methane and nitrogen oxide anthropogenic emissions of any other waste or industry in the UK at 40%, 22.5% and 28% respectively. With large scale implementation for on-farm AD, mitigations for 90% and 50% of methane and nitrogen oxide could be achieved with the added potential of generating more than 1.615 TWh of sustainable electricity. Further processing and changing application methods of slurry and muck to land is required to reduce ammonia emissions. Barriers in the form of insufficiently high banding and tariff systems, planning, high capital costs, lack of government subsidies and low gas yields prevent this. Therefore, it would be suggested that a lower high paying tariff banding system needs to be introduced to increase AD plants on farms. It is suggested an addition of a gate fee payment to reduce high energy crops used as supplements for gas yield, and to increase the amount of slurry and muck that are digested. The bespoke nature of farms could still present a fundamental issue in the degree manure and muck in the UK are processed.

The use of biomass capital to decarbonize the UK energy market has considerable potential, and the use of sustainable biomass waste and residues can be part of this solution, both in the direct processing of liquid and gaseous fuels as well as in the supply of renewable electricity generation capacity to decarbonize the UK grid and (indirectly) power a possible fleet of electric cars. Fostering the use of wastes and residues to create jobs in the UK also has considerable value. This is especially true for the AD industry where anaerobic digesters are widely distributed throughout the country, including in rural areas. There is also a need for the UK Government to step up measures to ensure efficient waste and residue production and we recommend a combination of responses including:

- Supporting effective EU policy reforms to promote a transition from traditional energy to sufficient advanced bioenergy from waste and residues;
- Formulating specific protections to follow the usage of waste and residues in the energy and transport field, notably in the absence of protections established at EU level as part of the existing Renewable Energy Directive adjustment procedure. A crucial precaution is the development of the required carbon accounting system for waste and residues, taking proper account of shifts in soil carbon supplies (e.g. in relation to straw extraction). The design of these protections will profit from cross-departmental collaboration to insure, in particular, that waste management priorities are not undermined;

- Research commissioning to enhance the perception of target applications for waste and pollutants, taking into consideration the business condition in the United Kingdom with regard to domestically accessible production and current applications (energy and non-energy). This would also create more accurate figures of the quantity of waste and contaminants that may be applicable to the energy and transport industry. Although we have established the feedstocks that currently tend to be more renewable, their processing into biofuels or biomethane might not be the more 'sustainable' usage, for example in terms of the total GHG emissions avoided;
- Cross-sectoral guidance on encouraging safe management and handling of waste and residues. Cooperation amongst policy departments collaborating on sectoral policies (agriculture, forestry, waste) and establishing targets for green energy and transport policies is required to ensure that policies in various sectors are complementary. It will result in valuable guidance to the various sectors and stakeholders and cause collaboration between, for example, producers, forest owners, waste processors and bioenergy or AD plant operators;
- Providing funding resources to develop emerging waste-to-energy processing technology. It would possibly involve capital funding for new projects, as well as help for current infrastructure growth. This would help increasing the potential of waste-to-energy processing and enjoy the advantages of technical innovation to reduce the costs of emerging technology.

Initiatives in these directions would be required not only to promote the development of an innovative waste-to - energy sector, but also to establish an acceptable route for the wider usage of bioenergy and biomass. There is an ability to reap several benefits by producing more green electricity, improving engineering know-how, and creating economic benefits like a large amount of potential jobs by turning waste and residue currently underutilised into beneficial uses. If protections are introduced, the environmental advantages of switching away from traditional biofuels in decarbonizing the UK energy and transport market would improve.

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Waste-to-energy conversion technologies in the UK: processes and barriers – a review

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Abstract: This paper reviews the sector of waste-to-energy looking at the main processes and feedstock involved. Within this, incineration, gasification, pyrolysis, anaerobic digestion and hydrothermal liquefaction are named and discussed. Through the discussions and scrutiny, manure is highlighted as a significant source of ammonia, methane, and nitrogen oxides emission, estimated to be 40%, 22.5% and 28% respectively of the total UK's anthropogenic emissions. Manure, and indeed the pollution it poses, are shown to remain largely ignored. In waste to energy processing, manure is capable of providing biogas for a number of pathways including electricity generation. Anaerobic digestion is highlighted as a suitable process with the crucial capability of drastically reducing the pollution potential of manure and slurry compared to no processing, with up to 90% reduction in methane and 50% reduction in nitrogen oxide emissions. If the majority of the 90 million tonnes of manure and slurry in the UK were to be processed through biogas harvesting, this could have the potential of producing more than 1.615 TWh of electricity. As such, the economics and legislation surrounding the implementation of anaerobic digestion for manure and slurry are discussed. In the end, restraining factors that limit the implementation of anaerobic digesters on farms in the UK are discussed. These are found to be mainly capital costs, lack of grants, insufficiently high tariff systems, rather than low gas yields from manure and slurry.

Keywords: waste feedstock; manure; anaerobic digestion; waste-to-energy

1. Introduction

The need to become more sustainable through the threat of global climate change and resource depletion is ever more prominent. Coupled with an ever-increasing population, rapid industrialisation, depleting fossil fuel resources present significant biowaste disposal and energy demand problems. In the UK, around 7.4 million tonnes of biodegradable municipal waste were sent to landfill in 2017 [1]. This waste could otherwise have been processed and recycled. The environmental impact of biodegradable waste extends beyond increasing greenhouse gasses due to the decomposition process. Untreated biodegradable waste release unpleasant odours due to decomposition and attracts scavenger animals and pests [2]. This has an impact on general public health and changes the biodiversity in the surrounding areas. Leaching from landfills not only contaminates the groundwater but can also affect the adjacent soil quality. In EU legislation, it is stipulated that biodegradable waste ending up at landfill must be reduced by 35% by 2020 compared to 1995 levels. This is one example of the driving forces behind waste to energy (WtE) processing, focused on reducing the volume of waste, recovering valuable products and producing electricity.

The term 'waste-to-energy' can be used interchangeably and encompass a variety of processes and technologies. The conversion of waste into energy will be analysed in this paper by the following processes: incineration, gasification, pyrolysis, anaerobic digestion, and hydrothermal liquefaction. The schematics of waste to energy processes are shown in Figure 1.

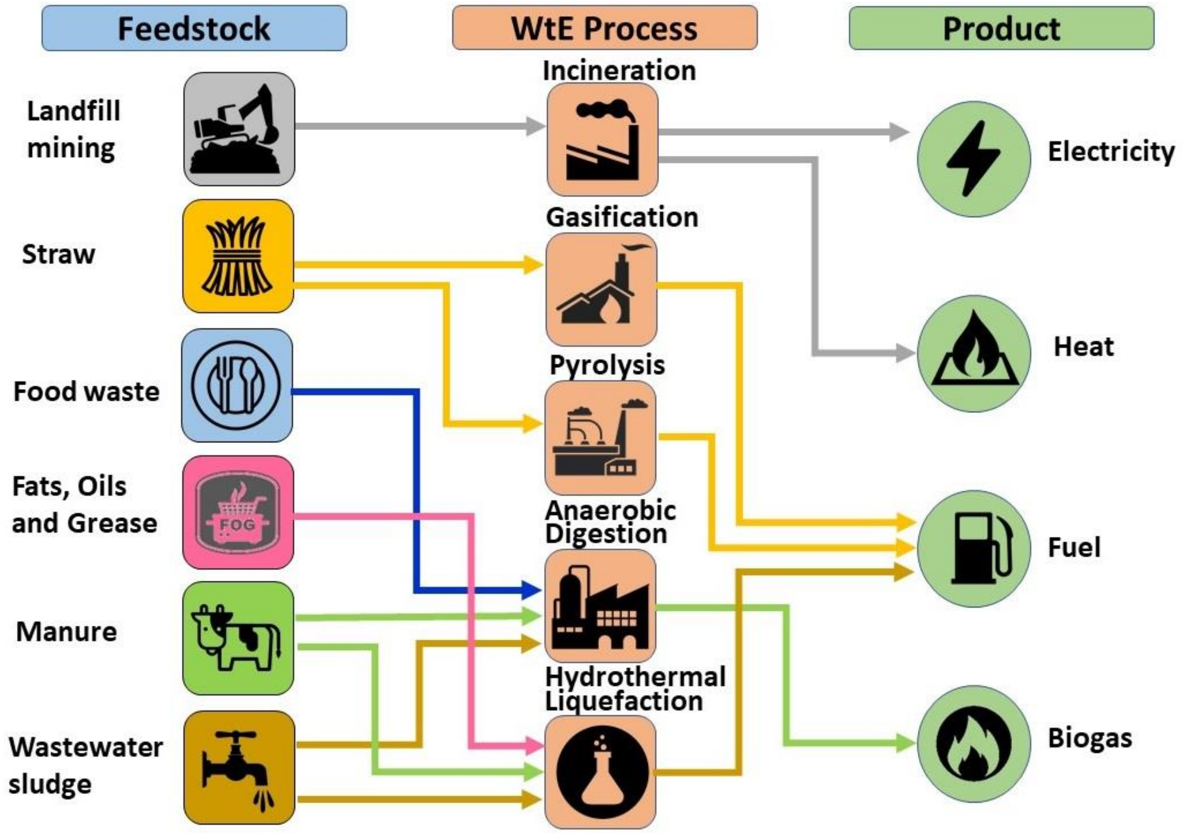


Figure 1. Schematics of waste-to-energy processes

Incineration is known as the complete oxidation within a waste stream of combustible materials and operates as temperatures above 850 °C. All feedstocks of waste addressed in this paper can be incinerated. This is one of the key advantages of incineration, the ability to deal with a diversity of wastes. Gasification in many sectors has been operating worldwide on a large basis for more than 80 years. During high temperatures (500 – 1800 °C), partial oxidation is accomplished by reducing the access to oxygen. The gases produced known as 'syngas' do not burn but can be gathered and processed for subsequent use. Pyrolysis operates similarly to gasification where partial oxidation is used to maintain thermal conditions. While this development is not new, a widespread deployment has not yet been accomplished. The process operates at about 300-700 °C. Anaerobic Digestion (AD) is an established process for the treatment of organic waste within the waste to energy sector. In 2007 the Department for Environment, Food and Rural Affairs recommended companies in England and Wales to use AD to better achieve electricity goals. Interest decreased because of concerns about economic viability. AD is still considered a key process for achieving a circular economy, increasing resource-efficiency and for the bioenergy-economy. Hydrothermal liquefaction is the thermochemical conversion of biomass into biocrude oil that can then be refined into petroleum derived fuels. The process is conducted in a 4 to 22 MPa pressurised environment at temperatures 250-374 °C. With promising biomass yields this process can become more widespread in the future in the waste-to-energy sector.

The rise in WtE has contributed to energy recovery increases in the UK with tonnage of processed wastes up to 7.3 million in 2018, nearly 4 times that of 2014 at 1.9 million [1]. The estimated range of total biological waste in the UK in 2020, including forestry residue and sewage sludge waste streams, amounts to 406.86 PJ, as shown in Table 1.

Table 1. Summary of UK maximum estimates of potential for biological waste streams

Waste stream	Petajoule [PJ]	Reference

Renewable fraction of waste	43.7	[3]
Straw	132	[4]
	88.5	[5]
Food waste	46.9	[3]
	38	[4]
Green waste	10	[4]
Livestock manure	16.4	[3]
Sewage sludge	12.4	[3]
Used cooking oil	9.66	[4]
Forestry residues	8.3	[3]
	19.2	[6]
Arboricultural arisings	46	[3]
Landscape care wood	35.8	[6]
Total	406.86	

*1 Mtoe = 41.868 PJ

Large amounts of waste are now processed at facilities capable of energy production. On top of this, wastes once discarded into landfills through enhanced landfill mining, can be dealt with past and present, altering previous perceptions of what a landfill is, considering them simply as ''temporary storage awaiting further processing'' [7], with vast amounts of valuable materials and heavy metals that can be recovered. The waste generated worldwide is losing its potential contribution to sustainable living. Therefore, this paper looks to review the different wastes and the processes involved in WtE and assessing process capabilities and waste streams that can be incorporated. It also looks at the question on what more can be done and what if any significant waste streams remained untapped or not utilized to their full potential, how this can cause significant environmental and sustainable problems.

This paper also emphasizes on manure that has great potential to be used as energy source in anaerobic digesters if implemented on small scales at local farms. A global concern is poor production and utilisation of nitrogen (N), phosphorus (P), and potassium (K) from livestock [8]. Organic matter and nutrients recycled in manure are essential for agricultural soil structure and nutrient content [9]. Manure has a natural nitrogen and phosphorus content so if it is not utilised as a fertiliser on agriculture, natural nutrient cycles are disrupted, possibly that nutrient leaching, so artificial fertiliser needs are generated. Nitrogen fertiliser processing requires extensive usage of natural gas and produces pollution that lead to global warming [10]. In addition, it is stated that existing usage of small phosphate supplies for phosphorus fertiliser is unsustainable [11]. Therefore, some issues may be mitigated by rising the use of artificial fertiliser by reusing manure.

On the other hand, the vast quantities of excreta produced in localised areas will add to the nutrient excess at the regional level [12]. Excessive use of manure as an organic fertiliser can contribute to soil and water eutrophication, pathogen transmission, air contamination, and greenhouse gas emissions [13]. Sustainable processing of these large units of output is only possible if manure is reused properly. Composting is a potential stabilising procedure. A significant drawback, though, is the strong nitrogen depletion. This phenomenon decreases the fertiliser benefit and may cause odour disturbance and present a serious environmental threat [14]. An option to eco-friendly treatment is anaerobic digestion (AD), which provides added advantage to restore the caloric content by biogas production. Unfortunately, manure 's strong nitrogen content is prohibitive to successful AD. Organic Nitrogen is transformed to ammonia through microbial degradation. Ammonia exerts a strong inhibitory influence on microbiological conversion at high concentrations. Non-dissociated free ammonia triggers the toxicity [15, 16]. This compound diffuses into cells, causing a proton imbalance or interfering with microorganisms' metabolic enzymes [17]. Overcoming ammonia inhibition is essential to effective manure AD.

To make this implementation feasible and sustainable, we have highlighted the need for further processing and changing application methods of slurry and muck to land as a requirement to reduce

ammonia, methane and NOx emissions. The paper also discusses the barriers in the form of inadequate high banding tariff and systems, planning, high capital costs, lack of government subsidies and low biogas yields. It has been suggested that a lower high-paying tariff banding system needs to be introduced to increase anaerobic digestion plants on farms. It is required addition of a gate fee payment to reduce the high energy crops use as supplements for biogas yield, and to increase the amount of slurry and muck that are digested. The paper also discusses the bespoke nature of anaerobic digesters on farms and the scales of anaerobic digestion plants. The value of this paper is that it has reviewed different challenges and aspects of implementation of anaerobic digestion systems on farms within a framework of waste-to-energy conversion.

In addition to technological and environmental prospects of WtE, previous studies also tried to understand social acceptance of wate to energy and renewable energy technology. Shackley et al. [18] performed work on carbon dioxide absorption and storage in Europe and found that most of the respondents accepted this issue under the regional CO_2 mitigation plan. Wolsink [19] points out that including local citizens in the policymaking phase would help strengthen the policies on social acceptance and that without societal recognition it is difficult to accomplish both waste-to - energy and sustainability targets. Social tolerance also has to be taken into consideration through decision formation. The three reasons for popular resistance to renewable energy technology were stated by Rogers et al. [20]: inadequate growth size, unreasonable cost-to-public benefit ratio and the lack of proper connexion between the local people and their views. Wang et al [21] analysed the waste management engagement in China, as well as how waste processing, sorting, collection, cost, age and education impact waste sorting satisfaction. They also examined the impact of satisfaction on participation in terms of enthusiasm, social contact and active involvement between region and gender by using systemic equation analysis from multiple communities.

To summarize what was mentioned above, we want to emphasize that this paper is a first attempt to look at the waste-to-energy that reviews the status of different WtE technologies in the UK, including the incineration, gasification, pyrolysis, anaerobic digestion and hydrothermal liquefaction. The reviews [1-6] mentioned above highlighted the expected amount of different types of waste in the UK that would be available by 2020 but did not specify the processes to treat these types of waste. The reviews [8-11] discussed the importance of using manure as an organic fertiliser and also the importance of pre-treatment of manure by using AD to avoid environmental impacts associated with soil and water eutrophication, pathogen transmission, air contamination, greenhouse gas emissions and overcoming the ammonia inhibition of AD processes [12-17]. However, these reviews did not discuss the potential barriers associated with the economic aspects of AD such as tariffs, incentives and implementation of AD in farms. Therefore, the aim of this review is to cover the current status of WtE in the UK, understand its limitations, advantages, environmental effects, identify challenges in regards to the implementation of the waste, and assess what can be done to further utilize waste to energy in the effort to reduce pollution, resolve waste disposal issues and address energy needs.

2. Sources of waste feedstock

There is a significant discussion on the sustainability of bioenergy in Europe and the United Kingdom in particular, sparked by the recognition that increasing bioenergy use has larger environmental and social effects than was previously expected. The effect of expanded crop production for bioenergy usage on land use and the implications for the bioenergy profile of greenhouse gas (GHG) are significant environmental concerns. Increasing global demand for main grains and other crops for bioenergy processing results in increased competition on global agriculture markets, which decreases food prices to differing degrees [22]. This coupled with land purchases from primarily subsistence farmers for the development of large-scale bioenergy crops is the primary source of worry over the social impacts of traditional bioenergy.

The bioenergy produced from waste and residues is considered a way to boost environmental and social efficiency and industry credibility and to save more GHGs than conventional energy. Nonetheless, there are concerns about the viability of other feedstocks and the amounts of biomass accessible to the bioenergy industry as a feedstock. Considering that the UK energy market must be decarbonized, it is important to consider 1) possible domestic waste and residue that can help minimise the effect of UK biofuel use on biologically, socially and economically, including the ILUC impacts from outside the UK; 2) sustainable waste and residue amounts that could be required in advanced processing of biofuel; 3) the growth of job opportunities in the United Kingdom as a consequence of setting up a bioenergy industry in sustainable development.

2.1 Biomass waste

The efficient use of biomass waste offers an extensive range of advantages. Apart from fulfilling the requirements of public services, biomass can be a tap alternative sources of carbon and play a key role in a production energy system using renewable sources without decreasing food and feed stocks. There exists a great variety of biomass waste that can be used for bioenergy production. One common type is straw, which is a by-product of the cereals harvest, but the definition may be further specified to include oil-seed rape grain and maize-growing 'substantive.' There are a variety of common applications both in the farming industry and beyond. The large-scale usage as field improvement, livestock bedding and the substitute for fodder are significant applications in the UK. Straw is also used for mushroom and horticultural production. Apart from growing, straw is used as stalk and more commonly as a building medium and for direct combustion for heat and electricity production.

As a bioenergy feedstock, the sustainability of straw is highly linked to its scale, its location and removal from current applications which can benefit from their own impact. Kretschmer et al [22] address the potential for European straw usage as well as the adverse effects of excessive straw diversion on energy usage, including: the degraded capacity of the soil, particularly through a reduction of organic soil content and consequently of nutrients; potential long lasting impacts on fauna arising from shifts in stubble heights and straw control and impact on livestock health because there is no readily accessible option to roughage and bedding (like sawdust or wood chipping). For 2020, multiple reports forecast the availability and order of straw for different purposes. As Table 1 shows, the results vary greatly. One potential explanation is the challenge of taking into account regional differences. Depending on these reports, the amount of 18 to 132 PJ of straw for UK bioenergy output was predicted for 2020 by Smith [4]. The UK's straw capacity is 88.5 PJ from a European report that offers forecasts for different countries [5].

Another type of biomass waste is woody residues. Smith [4] stated that most of the UK 's new forestry (roundwoods and residues) products were recycled into the sawmill industry and the panelboard industry. Given the high proportions of (mostly private) under management forests in the UK, however, the supply of residues is likely to increase significantly, with certain materials available for the energy sector as a feedstock. It may have positive side consequences, such as providing local work, which also contribute to habitat upgrades. Increasing the production of forestry residues by better management was one of the specified goals of the new forestry policies and strategies of the UK, in particular the Woodfuel Strategy and the Woodfuel Implementation Plan 2011-2014 of the Forestry Commission. It is expected to produce another two million renewable tonnes (residue and plant) of wood biomass each year by 2020 by: 1) Setting requirements for a profitable and safe wood fuel supply chain; 2) Capacity building by market growth and reduction of obstacles to forest management; 3) Ensure that, in close collaboration with the Biomass Energy Center (BEC), access to specialist expertise leads to business growth.

2.2. Landfill mining

This feedstock is the result of landfills 'reopening' to be extracted of their sources of valuable and combustible material wastes. As landfills are known to incorporate a large degree of different wastes, the exact chemical constitution can vary considerably. Prior to the European directive in 2001, there was little control in the way of what ended up in landfill sites, giving rise to concerns of hazardous wastes and indeed the effects to the environment [23]. That said typically plastics, organic wastes, different kinds of metals, textiles, wood and rubber are most commonly found in the feedstock based on the combinations of waste ending up at landfill. Table 2 gives a brief outline of these sources. These main raw materials may be mixed in with contaminates containing elements such as sulphur, chlorine and heavy metals. Bosmans et al. [7] showed that the presence of these elements can greatly affect the quality of the products produced though waste valorisation such as the syngas, bottom ash, fly ash, digestate and vitrified slag. Increasing the need of specialized abatement technologies required to reduce the amount of pollutants in the products or emissions to the atmosphere. These technologies take the form of flue gas cleaning systems.

Table 2. Different landfill waste streams

Source	**Types of different waste streams**
Commercial and Industrial waste (CaIW)	Paper, packaging, metals, tyres, textiles and biomass [24]
Municipal Solid Waste (MSW) (Household waste)	Paper, cardboard, metals, textiles, organics
Refuse Derived Fuel (RDF) (processed CaIW and MSW)	Separation of recyclables, non-combustibles from source. Shredding/size reduction may include pelletizing. Processing done to adhere to a fuel specification.
Solid Recovered Fuel (SRF)	Similar to RDF but less contaminated and more homogenous, adheres to more stringent specifications [25]
Scrap Yard Shredder Residue (SYSR)	High degree of plastic and mixtures, metals, rubber glass, wood, leather, textile, dirt and grit. Mainly result of automotive scrappage [26]

Note that the streams shown in Table 2 are in their own right different wastes that can be utilized for energy or product extraction if landfill is circumvented all together. Where Table 3 provides the typical properties that can be expected from MSW and RDF.

Table 3. Characteristics of MSW and RDF

Source	% C	% H	% N	% O	% VM	Lower heating value (MJ/kg)	% water	Ref
MSW	49.5	5.60	1.33	32.4	87.1	18.7	34.2	[7]
	35.8	4.8	0.78	24.3	67	15.2	32.4	[27]
	43.71	7.73	1.95	37.66	77.66	18.5	20	[28]
RDF	54.6	8.37	0.91	34.4	88.5	22.6	10.8	[7]
	48.2	6.4	1.22	28.4	75.9	17.8	20	[29]
	48.5	6.4	1.2	31.3	83.5	20.9	26.51	[30]
RDF (From landfill)	54.9	7.38	2.03	NA	80.4	22	14.4	[7]

2.3. Food waste

The definition of food waste is taken from Lebersorger and Scheinder [31] where it includes solid components from food preparation residues, post-preparation and consumption residues, part consumed food and whole unused food. The main sectors according to Skaggs et al. [32] from which this waste arises are firstly industrial food processing centres; secondly, institutions such as hospitals, universities, schools, prisons; thirdly, commercial enterprises such as restaurants, grocery stores, food distribution centres; and fourthly residential units. A degree of this waste is averted through a food waste recovery hierarchy before the level of energy and product extraction. This type of waste is known to be of high value in its uncontaminated state where a large part at the industrial level waste can be used to create animal feeds. The types different from the animal feeds are opened up to energy and combustible product extraction and through anaerobic digestion. Looking at published work, generally speaking, the degree to which the feedstock is valued revolves around the moisture content [33,34,35]. Where a lower moisture content increases the combustion characteristics and suitability to associated processes, also reduces energy loss through steam/drying. A higher moisture content increases suitability for digestion. Table 4 shows typical composition of food waste in UK.

Table 4. Characteristics of typical food waste

Source	% C*	% H*	% N*	% O*	% VM* Of TM	Higher heating value (HHV) (MJ/kg)	% Lipid	% Protein	% Carb	Ref
UK	52	6.9	3.1	38	22	22	15	21	48	[36]
Korea	51.2	7.2	2.9	38.1	-	-	-	-	-	[37]
Various	-	-	-	-	-	-	6.4-24.1	3.9-21.8	24-46.1	[38]
Malaysia	47.4	6.9	3.3	38.7	-	17.45	-	-	-	[39]

2.4. Fats, Oils and Grease (FOG)

Large institutional kitchens, restaurants, cafeterias are responsible for the production of waste/used oils, fats from animals and grease through cooking. A percentage of this waste inevitably ends up down sinks and in the sewers whereas they are non-water soluble can collect and form blockages. The Environmental Protection Agency (EPA) has estimated FOG build ups contribute to 70% of sewer pipe blockages and 30% of pump station failures [40]. Water UK [41] provides guidance on avoiding fats and oils from entering the sewers for large kitchens where grease traps are the primary means of capture. This works via taking advantage of the difference in density of water and FOG to capture and contain the grease to be disposed. This grease can contain a wide range of suspended waste food solids and wastewater, and as such, is known as ‘brown grease’. These contaminates make it more difficult to recycle than ‘yellow grease’ which is from spent oils and fats that have not interacted with wastewater i.e. deep fat frying. Due to this contamination, the brown grease is not used for biodiesel production due to lower energy content of 35 MJ/kg compared to 40 MJ/kg of waste cooking oil. [42]. So, the brown grease is usually disposed as waste rather than recycled into energy. There are many options in regards to utilizing yellow grease in anaerobic digestion, composting, processing into biodiesel as mentioned, or used as additives for animal feed and soap. But the uses of brown grease are not so clear with its hazardous classification and more difficult extraction procedures.

Other than waste oils, fats and grease from the cooking industry, a large amount of synthetic and mineral oil wastes accumulate when they are no longer deemed fit for purpose. These are motor oils, heating oils, hydraulic oils, ship oils, sump residue and oil-water emulsions. All categorized as hazardous waste due to the chemical makeups used. For example, used engine oil contains cocktail of hydrocarbons, heavy metals (magnesium, cobalt, zinc, iron), minerals, chlorine, sulphur, phosphorus, nitrogen and additives all known to have cancerous effects and detrimental to the environment [43]. The environment protection agency states that one drop of used motor oil can contaminate 1 cm^3 of water, highlighting the scale of potential cause when considering if all vehicles that have internal combustion engines produce waste oils.

2.5. Wastewater sludge (WWS)

During the processing and treatment of wastewater to return it to the environment, a residual nutrient rich semi-solid is produced known as wastewater sludge (WWS), typically containing 25-75% solid based on weight. WWS can be composed of solids from primary and secondary treatment stages. During the primary stage, the initial suspended solids within the wastewater are separated. Around 40-70% of solids within the wastewater are captured, where the organic and inorganic fines are concentrated down to 2-7% and 60-85% for volatile suspended solids. Secondary treatment stage focusses on biological aspects where a combination of aeration, exposure, microbes and secondary settling occurs. Solids are concentrated to 0.5-1.5% with volatile suspended solids concentrations at 70-80% [32]. Biochemical characteristics of primary and secondary sludge are shown in Table 5.

In the US approximately 6.3 million metric tons of municipal WWS was produced in 1998 of dry solid weight (according to the US environment protection agency) and todays figure will only be higher. When processed properly it can be very beneficial for the application of agricultural land to improve soil quality, using as a soil conditioner in landscaping, and using for part of landfill cover-ups [44]. Hence the term 'biosolids' is associated with processed WWS. The main energy recovery process associated with WWS is anaerobic digestion, in which the resultant bio-waste and indeed the treated WWS can be used in the production of biosolids for fertilizer. However, there are social concerns in regards to heavy metals and pharmaceutical compounds that could be within the WSS. Which, when introduced to agricultural cropping soils can give a predominately negative effect on local water, energy and material sustainability [45]. In addition to affecting the ecosystem through concentration of heavy metals, crucially highlighting contaminates play negative role in reducing the sustainability and product quality. An option that reroutes the biosolids from being used as fertilizers and averting the social concerns is hydrothermal liquefaction processing into bio crude oil. This bio crude oil can then be refined to meet bio diesel and diesel standards [46].

Table 5. Biochemical characteristics of primary and secondary sludge

Source	% C	% H	% N	% O	% VM	HHV (MJ/kg)	% Lipid	% Protein	% Carb	Ref
Primary sludge	47.8	6.5	3.64	33.6	82.17	20.7	-	-	-	[47]
	51.5	7.0	4.5	35.5	65	-	18	24	16	[48]
Secondary sludge	43.6	6.55	7.9	29.0	76.25	19.6	-	-	-	[47]
	52.5	6.0	7.5	33.0	67	-	8	36	17	[48]

2.6. Manure

This is the combination of animal faeces with an agricultural by product such as straw (used as animal bedding). All livestock, particularly indoor bred stock produce manure. This manure can vary in composition depending on the type of animal it is from and what diet they are on. Table 6 shows these differences in the biochemical characteristics.

Table 6. Characteristics of different manures at 76.37% water content

Source	% C	% H	% N	% O	% VM	HHV (MJ/kg)	% Lipid	% Protein	% Carb	Ref
Fattened cattle	35.38	3.73	2.38	57.51	16.21	15.16	6.8	26.6	52.5	[32]
Dairy cows	38.8	5.1	1.3	54.7	83.2	11.9	5	18.11	52.6	[32]

Bacon pigs	41.1	5.42	3.36	50.1	83.7	-	20.3	24.5	34.7	[32]

Fertilization is the primary use for this type of fully biodegradable waste where without any processing it is spread onto crop producing land. A common life cycle is known to be set up between arable and livestock farmers in the UK as a result where manure is exchanged for straw. Where the manure is desirable for arable farmers to fertilize their land and the straw from the crops produced by the arable can provide a bedding and food source for a livestock farmer [49]. This is the virtually at present the only pathway for disposing the manure and slurry. Processes such as anaerobic digestion (discussed in the next section) aim to tap into the vast amount of energy stored within this feed though emitted products. Nitrous oxides, methane and ammonia are the most prevalent gasses released into the atmosphere by the decomposing manure without any process intervention. This is of great concern given the amount of manure produced every year and known the global warming characteristics of said gasses. The animal agriculture sector accounts for 37% and 64% of the annual anthropogenic methane and nitrogen oxides emissions, respectively, which are 23 and 296 times the global warming potential (GWP) of carbon dioxide. In addition, livestock are responsible for 64% of the anthropogenic ammonia emissions, contributing to the formation of acid rain and acidification of ecosystems [50]. Such high percentages are alarming considering that the majority of these emissions are from manure and slurry and highlight the need for processing to bring emissions in the sector to some acceptable level.

3. Waste-to-Energy Processes

Waste-to-energy encompasses a variety of specific methods and technologies. In the purposes of this article, this is intended to identify a variety of disposal methods and techniques utilised to produce a functional source of energy and to minimise the amount of residual waste. Such energy may be in the form of power, heating and/or cooling, or turning the waste into a product for potential usage, such as biogas, automotive fuels, or a mixture of these types. In this paper we will review the conversion of waste to energy through the following processes: incineration, gasification, pyrolysis, anaerobic digestion, and hydrothermal liquefaction.

3.1. Incineration

Incineration is classified as the full oxidation of the combustible materials within a waste stream. The process is composed of several key stages of drying/degassing, pyrolysis and gasification then combustion. Unlike other processes in this list that only partially oxidize the waste stream, incineration can be fed by a large variety of waste streams. In fact, all waste streams discussed in this paper can be incinerated. This is one of the main advantages incineration has, the ability to deal with a high degree of waste variety. The variety effects the product percentages left after processing, such as the bottom ash which in MSW incinerators is approximately 25-30 % by weigh of dry waste input, and the fly ash is at 1-5 %. The fly ash requires immobilization to be made environmentally safe, which can then be used in asphalt concrete. The bottom ash however requires much more processing, where at a slag reprocessing pilot plant facility, valuable metals (Al, Fe, Cu) can be recovered. The residue after metal recovery can then be granulated for the construction industry [51]. Figure 2 is an example diagram of a combined heat and power (CHP) plant based on incineration.

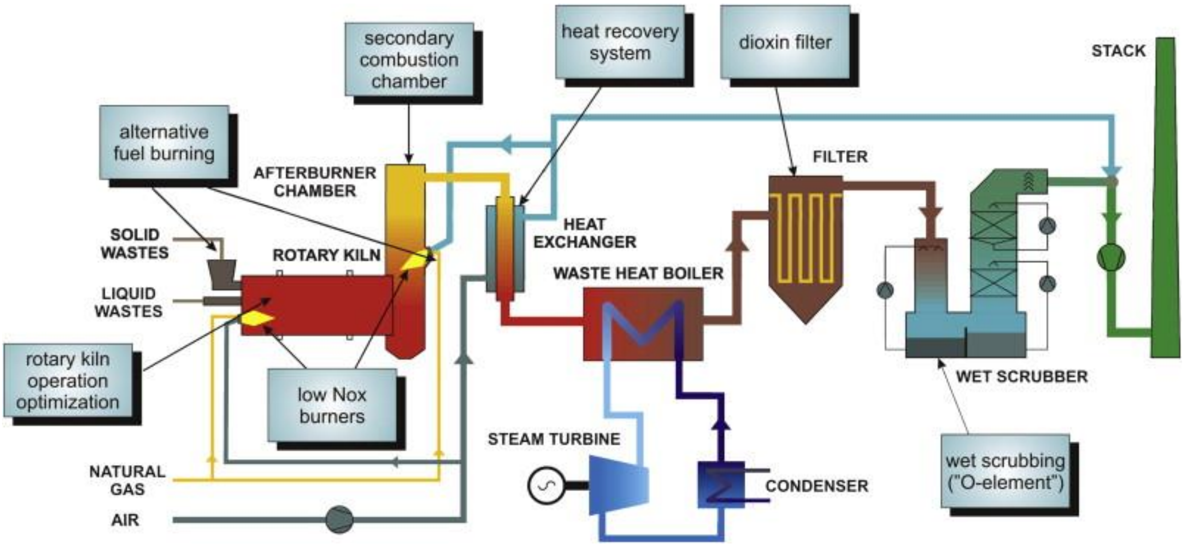


Figure 2. Simplified layout of a waste-to-energy incinerator [51]

Originally, incineration was purely used to reduce the volume of waste as well as destroy harmful substances in the effort to prevent health threats. Now, waste incineration is predominantly combined with energy recovery the importance of which is increasing. Denmark and Sweden are notably the world leaders having produced electricity from the incineration of waste for more than 100 years [52]. Now there are 3 main types of incinerators; gate, rotary kilns and fluidized beds, each type specified for particular feedstock. The plant efficiency factor of these incinerators according to the confederation of European WtE plants (CEWEP) in 2010 based on accounted 314 plants was at average 0.69. The specific electricity produced as weighted average was 14.89% of total Mg and heat at 34.59% of total Mg [53]. Note that the Plant Efficiency Factor ($R1$) in the equation (1) was used to obtain the figures given in accordance with the waste frame directive [54]. WtE plants "producing electricity only" have the lowest $R1$ factor of 0.55, as a non-weighted average, so that only 37.3% plants reach $R1 \geq 0.60$. Although WtE plants "producing heat only" have a higher $R1$ factor of 0.64, as a non-weighted average, only 68.1% plants reach R1 ≥ 0.60. In this case, the import of the total amount of electricity to treat the waste has a negative influence. WtE plants "CHP producing" achieve the highest $R1$ factor of 0.76, as a non-weighted average, so that 77.2% plants reach $R1 \geq 0.60$.

$$R1 = \frac{(E_p - (E_f + E_i)}{\left(0.97 \cdot \left(E_w + E_f\right)\right)} \tag{1}$$

where, $R1$ - plant efficiency factor, E_p - annual energy produced as heat or electricity, E_w - annual energy contained in the treated waste, E_i - annual energy imported, and E_f - annual energy input to the system from fuels contributing to the production of steam [53]. These plants are notably still less efficient than conventional power plants. This is in part due to specific equipment requirements for incineration of waste, limitations on steam pressures due to corrosion risks, energy requirements to maintain optimal operational regime and critically pollution control equipment necessary to treat flue gasses. Generally, the more effective and complex a pollution control system is the higher the energy needs.

The current status of this technology in the UK is at TRL 9 since the actual system is proven in an operational environment. In 2016 there were 115 incineration facilities in the UK. It is estimated that 6.1% of waste generated in the UK is processed through incineration [55, 56]. 37 incineration facilities were fitted for energy recovery accounting for 3.4% of waste processing, as shown in Table 7. This equates to 7.3 million tonnes of waste. It is in increase from 2014 where only 0.9% of waste were processed with energy recovery representing 1.9 million tonnes of waste. Three new facilities were commissioned between 2014 and 2016, however, the total number of incineration facilities with energy recovery increased by eight. It is likely that new facilities are designed for energy recovery, while older facilities without energy recovery are converting to enable energy recovery. It is foreseeable that the number of incineration facilities with energy recovery will increase over the next decade as older facilities are converted.

Table 7. Use and capacity of incineration facilities in the United Kingdom [55, 56]

Incineration in the United Kingdom								
	Incineration only				Incineration with energy recovery			
Year	Mt	Capacity Mt/yr	% of all waste	Number of facilities	Mt	Capacity Mt/yr	% of all waste	Number of facilities
2012	5.9	8.4	3.1%	87	1.6	2.9	0.8%	27
2014	7.6	9.9	3.7%	83	1.9	4.9	0.9%	29
2016	5.7	8.5	2.7%	78	7.3	9.8	3.4%	37

The UK Strategy for Recourses and Waste reported that 3.4% renewable energy was generated from incineration of biodegradable waste in 2017 [57]. It is estimated that 2.3% of the UK's energy demand can be met through incineration with energy recovery should all the municipal solid waste that are currently sent to landfills be rerouted to incineration facilities [58]. Not only will this have a positive effect on the renewable energy generation in the UK, but also on greenhouse gas emissions generated from landfills. It is plausible that greenhouse gas emissions can be reduced by 2 million tonnes in this manner [106]. Legislation requires that biodegradable waste sent to landfills must be significantly reduced. This will see more municipal solid waste rerouted to incinerators providing an increase in feedstock and more opportunity for energy recovery from incineration. However, the current stance of the UK Government is that although incineration plays an important role in waste management the focus should be on prevention and recycling rather than landfills and incinerators. Taxation on the incineration of waste is likely to increase over the next few years which may reduce the economic benefit of this manner of waste management.

3.2. Gasification

Gasification has been around for some time more than 80 years globally on a commercial scale in many industries and 35 years in the power generation. In partial oxidation process of organic substances, high temperatures of around 500-1800 °C are used. Partial oxidation is achieved by limiting the oxygen exposure at those temperatures so the gases produced known as 'syngas' do not combust but instead can be collected and stored for later use. These later uses include the chemical industry, as a fuel for the production of heat and or electricity or conversion into ethanol [59]. The syngas constitutes of H_2, CH_4, CO, CO_2, H_2O and N_2 with trace amounts of other hydrocarbons like propane and ethane. Predominantly air is supplied to the reaction site which in comparison to using pure oxygen results in a syngas of lower energy. Such that, in terms of heating value, pure oxygen gives 8.7 - 11.3 MJ/Nm^3 and air gives 4–7 MJ/Nm^3 [60]. There are 3 main types of gasifiers: fluidized bed, fixed bed and entrained flow which are capable of dealing with MSW, dried sewage sludge, some types of hazardous wastes and waste food among others. One of the key requirements for the feedstock is that it must be finely granulated, therefore MSW for instance requires pre-treatment. This is a clear negative side when compared to incineration, which comparatively has lower residue percentage of the feedstock. But there are positive comparisons such as lower volumes of gases produced mean smaller flue gas treatment systems can be used and smaller wastewater flows from syngas cleaning [7]. In addition, the overall thermal efficiency is more than 75% [61]. Furthermore, by the use of partial oxidisation, the amount of oxidized species such as SOx and NOx are reduced, which are replaced by H_2S, nitrogen and ammonia. Known to be better forms that can be scrubbed from the syngas than the oxidized versions prior to syngas utilization [62].

In terms of gasification process a number of sub process take place. These constitute of a degree of pre-processing to remove inorganics such as metals and glass, which cannot be gasified, particle size reduction, drying (within the gasifier and in some cases prior to), oxidation and syngas collection. As can be seen the main waste product left over is slag (in high temperature gasifiers), this is similar to the bottom ash in the incineration process where metals and other valuable products can be recovered. Gasification of fossil feedstocks is an established process and is therefore rated at TRL 9. The use of biomass feedstock, such as municipal solid waste, is not readily applied in the UK. Although there are a number of plant in Norway, Germany, Finland, Italy and Sweden [63]. It was recently reported that operation had begun at UK's first municipal solid waste gasification plant located in Aldridge [64, 65]. To date the plant is operating on waste wood feedstock and the technology is not proven for municipal solid waste, although it is the intension to do so in the future. This is not the first gasification plant constructed in the UK for processing of biomass waste. Several such facilities have been built in the past and all have failed [66, 67]. One such example is the company Energos Ltd. that operated a gasification plant in the Isle of Wight since 2009 [68]. The plant made use of Refuse Derived Fuel (RDF) and was designed to provide 1.8 MWe power. The company had plans to build similar plants in Glasgow, Milton Keynes and Derby. However, the plant went into administration in 2016; the route cause was found to be a failure to deliver on gasification contracts. Another example is Ascot Environmental and its subsidiaries Planet Advantage and Scotgen that build a gasification plant in Dumfries in 2009. The plant was designed to deliver 6.2 MWe power from municipal solid waste and RDF feedstock. The company filed for administration in 2012 since the plant failed to produce energy during its three years of operation. The permit to operate that plant was revoked due to non-compliancy with the Scottish Environmental Protection Agency.

Fiscal incentives for the development of advanced conversion technologies, such a gasification of municipal waste, might receive more attention in the next decade [69]. The Engineering and Physical Sciences Research Council (EPSRC) does not have a specific research focus in this area but has supported gasification projects in the past [70]. Considering the past failures of the technology, it will be challenging to obtain the necessary funding to increase the TRL. Much depends on the operation and economic viability of the Aldridge plant and its ability to robustly process municipal solid waste on a large scale. The success of this plant will unlock the potential for gasification as biowaste processor. The failure however, along with the historical failure of similar plants, will be seen as conclusive proof that further development of this technology should be abandoned.

3.3. Pyrolysis

This process works on the thermal degradation similarly to gasification where partial oxidation is used to maintain the thermal conditions. Pyrolysis can also be achieved in complete absence of oxygen with an external heat source in inert conditions. Comparatively to gasification, pyrolysis works on lower temperatures of around 300 - 700 ℃ [71]. To date, although this technology is not new, it has not yet reached a widespread implementation. During the process, 3 products are made: solid coke, pyrolysis gas, pyrolysis liquid. The exact constitution and proportions of these products depends on the feedstock, reactor conditions, reactant residence time and pyrolysis method. The process can be optimized to maximize the formation of each product [72]. For example, in the case of fluidized bed reactors (fast pyrolysis), high temperature and high biomass residence time increases the production of gases; On the contrary, high temperature and low residence time however increases the formation of condensable liquid oils; then low temperature and high residence increases the production of solid coke. Typically, the pyrolysis gas, liquid and coke have calorific values of 5-16 MJ/kg, 22-25 MJ/kg and 33 MJ/kg respectively. The low heating values of the gases and liquids mean that upgrading is necessary to produce fossil fuel substitutes [73]. Pyrolysis can work on any hydrocarbon waste that can be cracked to release gasses, oils and char. For instance, FOG, MSW, food waste, manure and sewage sludge are all acceptable.

One of the notable advantages of pyrolysis against other waste-to-energy processes is the higher energy density achievable of the products produced. But what some researchers don't mention is that these higher energy products were produced with external heat sources supplied to the reactor.

Furthermore, a degree of preparation is required to reduce feedstock particle size. Also, drying can be required depending on moisture content and the desired calorific value of the products. The inner stages are centralized around the reactions (thermal cracking) of the waste to release the pyrolysis products, which are then captured through condensing. The remaining coke is sometimes incinerated to rid of the organic matter remaining. Main pyrolysis reactor types include rotary kiln, fluidized bed, fixed bed, entrance flow, moving bed and more experimentally auger [74]. As hinted here, this process can be responsible of higher waste residue than gasification and incineration. This is mainly due to lower temperatures as a result of lower flue gas volumes after combustion of the products than incinerators [7].

As a general process, fast pyrolysis is currently deployed in operational environments with system completion and qualification. This places fast pyrolysis at TRL 8. Pyrolysis with upgrading, that increase the quality for the oil produced so that it can be used as transport fuel, is currently at TRL 5 [70]. There are 8 companies and 9 universities actively engaged in activities related to waste treatment through pyrolysis (Table 8). Activities are mostly aimed at waste-to-fuel applications instead of waste-to-energy. There are currently no large-scale facilities for pyrolysis in the UK.

Table 8. UK Companies and institutions involvement in pyrolysis

Company/Institution	**Location**	**Feedstock**	**Conversion**	**Ref**
2G BioPOWER	Kent	Tyre	Recycling	[75]
Anergy Ltd	London	Biomass	Waste-to-Energy	[76]
Conversion and Resource Evaluation (CARE) Ltd	Down	Biomass	Waste-to-Fuel	[75]
Cynar Plc	London	Plastic	Waste-to-Fuel	[76]
Environmental Power International	Surrey	Various	Waste-to-Fuel	[76]
Future Blends Ltd	Oxfordshire	Biomass	Waste-to-Fuel	[75]
PYREG (UK)	Cambridge	Sewage Sludge	Phosphorous Recovery	[75]
Torftech Energy Ltd	Thatcham	Biomass	Waste-to-Energy Waste-to-Fuel	[75]
Aberystwyth University	Aberystwyth	Biomass	Waste-to-Fuel	[75]
Aston University	Birmingham	Biomass	Waste-to-Fuel	[77, 78]
Newcastle University	Newcastle	Biomass	Waste-to-Fuel	[75, 79]
University College London	London	Plastic	Waste-to-Fuel	[80, 81]
University of Cambridge	Cambridge	Various	Material Recovery Waste-to-Fuel	[75, 82]
University of Edinburgh	Edinburgh	Biomass	Waste-to-Fuel	[83, 84]
University of Leeds	Leeds	Biomass	Waste-to-Fuel	[85]
University of Sheffield	Sheffield	Biomass	Waste-to-Fuel	[86, 87]
University of York	York	Biomass	Waste-to-Fuel	[88]

The EPSRC are routinely funding research aimed the development of bioenergy. The bioenergy thematical area currently holds 14 research grants worth £12,511,100.00. There are a number of grants awarded that is specifically aimed at improving the pyrolysis process. These were all related to waste-to-fuel applications focusing on upgrading the quality of products to be used as marine and aviation fuel. Funding for waste-to-energy applications of pyrolysis remains uncommon. The financial and technical challenges will hamper the integration of pyrolysis as a process for waste management in the next decade. Pyrolysis as waste-to-energy mechanism is subjected to technical challenges [68]. The feedstock from municipal solid waste is inconsistent and will need significant preprocessing before it can be used. Blockages are often caused in pyrolysis plants due to tar deposition which lead to inefficiencies. Catalyst deactivation and choking can result in plant failure. These challenges are not negligible and has led to the limited application of this process worldwide.

3.4. Anaerobic digestion (AD)

As with incineration and gasification, Anaerobic Digestion (AD) is a well-established process within the waste to energy sector for the treatment of organic wastes. Dating back to the 1800s making it one of the oldest waste to energy processes. The concerns around the environment has increased its utilization when in 2007 England and Wales businesses were encouraged to use AD by the department for environment, food and rural affairs (DEFRA) to help meet energy targets set by the government [89]. Now, however, interest has dropped due to economic viability concerns. Investments and interest primarily come from businesses such as farms and not large waste industry companies, as the case studies included in the Royal Agricultural Society of England report show [90]. One of the main differences between AD and incineration/gasification is the predominantly large plant waste treatment centres, costing hundreds of millions. However even with the economic concerns, AD is still considered a key process for achieving a circular economy, increasing resource-efficiency and for the bioenergy-economy as a whole [91].

The main feedstock for AD is manure and slurry, but it is not limited to these. Essentially, any organic matter can be fed into the digester such as WWS, FOG and food waste, as the process works on decomposition of organic matter. Microorganisms digest/eat the feedstock producing biogas, predominantly made up of methane (50-75%), with carbon dioxide along with traces of other gases making up the remaining percentage [92]. After the process, a solid mass known as digestate is left, a nutrients rich product that can be used as a fertilizer. As for the gasses produced, the high percentage of methane means it can either be upgraded to pure methane (main constitute of natural gas) or be combusted in a CHP plant. As Bywater [90] states ''The ratio of heat to power varies dependent on the scale and technology, but typically 35-40% is converted to electricity, 40-45% to heat and the balance lost as inefficiencies at various stages of the process, equating to over 2 kWh electricity and 2.5 kWh heat per cubic meter, at 60% methane''. There are two types of AD's: mesophilic and thermophilic, categorized according to their operation temperatures. The most common type (mesophilic) operate at temperatures between 20-45 °C. Thermophilic digester operates at higher temperatures and most commonly used for sanitizing materials, so that they can be used for the benefit of agriculture.

Anaerobic digestors are widely used in the UK placing the technology at TRL 9. There are currently 661 digestors operational in the UK [93]. It supplies the national grid with biomethane (102 plants) and electricity (583 plants) and provide local heating (42 plants). The feedstock varies from agricultural waste (374 digestors), municipal/commercial waste (113 digestors), industrial waste (48 digestors), and sewage sludge (163 digestors). Between 2008 and 2017, 255 new anaerobic digestors were built in the UK with a total capacity of 193,354 kW [92].

The percentage of energy generated in the UK from bioenergy is steadily increasing (Table 9). In 2010 3.5% of energy generated were from biological sources. This has increased to 9.4% in 2016. Anaerobic digestors forms a component of bioenergy and is increasing as well. In 2010, 117 GWh electricity was generated with AD, accounting for 1% of energy generated with bioenergy. This increased to 2052 GWh in 2016, which is 7% of energy generated with bioenergy. AD is further discussed in section 4 where the environmental, economic, legislative and implementation is investigated.

Table 9. Electricity generated in the UK from bioenergy by year [94]

Source	Units	2010	2011	2012	2013	2014	2015	2016
Landfill gas	GWh	5,217	5,318	5,208	5,175	5,033	4,872	4,703
Sewage sludge digestion	GWh	723	775	739	766	840	894	950
Energy from waste	GWh	1,529	1,504	1,773	1,648	1,900	2,585	2,741
Co-firing with fossil fuels	GWh	2,432	3,093	1,829	337	124	183	117
Animal Biomass	GWh	627	615	643	628	614	648	650
Anaerobic digestion	GWh	117	237	495	713	1,023	1,471	2,052
Plant Biomass	GWh	1,615	1,771	4,048	8,832	13,086	18,587	18,829
Total electricity generated from bioenergy	GWh	12,260	13,313	14,735	18,099	22,620	29,240	30,042
Total electricity generated from all sources	GWh	347,896	332,461	341,912	336,504	317,732	318,552	320,110

3.5. Hydrothermal Liquefaction (HTL)

This is the thermochemical conversion of biomass into oils referred to as 'biocrude oil' that can then be refined into petroleum derived fuels. The main advantage of this process is that water has a higher dissociation constant (and lower dielectric constant) at these operating conditions. The water is thereby less polar and helps to be a good solvent for hydrocarbon products and promote their reactions. As shown in Figure 3, the process is performed in a pressurized environment from 4 to 22 MPa, which avoids oxygen and heats to elevated temperatures between 250 - 374 °C [95]. These high pressures and temperatures help breakdown and reform biomass macromolecules into biocrude oil.

As with anaerobic digestion, the process provides a means for processing wet biomass without drying that incineration, gasification and pyrolysis require. However, HTL is essentially pyrolysis in hot liquid water. As such, feedstock high in water content are suitable i.e. manure and sewage sludge. HTL biocrude oils contain a diverse range of chemical compounds, which present major challenges for downstream processes. This in some instances due to high heteroatom content in the biocrude oil can result in undesirable qualities, like acidity [96]. That said significant amounts of biocrude oil can be obtained from pig manure and digestate sludge. Vardon et al. [96] showed that at 300 °C, 10-12 MPa and 30 min reaction time, pig manure and digestate sludge yielded 30% and 9.4% respectively with HHV's of 34.7 MJ/kg and 32 MJ/kg. With promising yields from biomasses, this process may become more widespread in the waste-to-energy sector in the future.

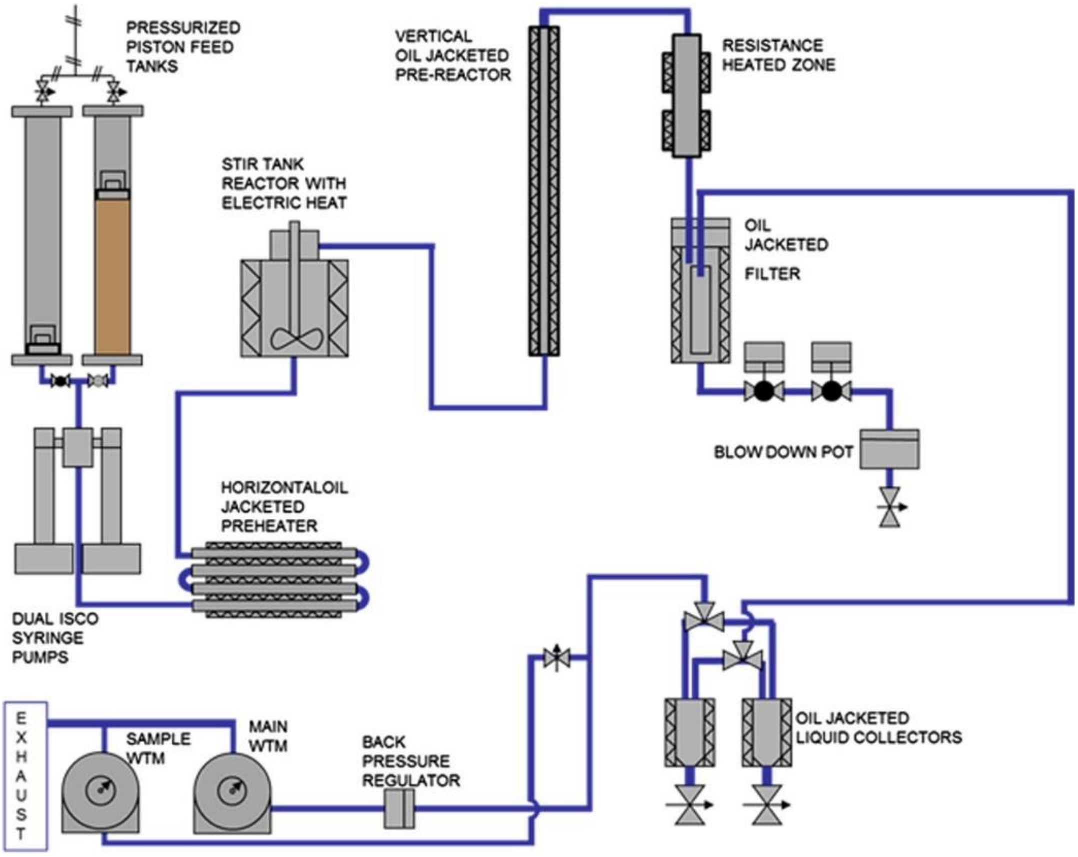


Figure 3. Diagram of HTL reactor system [95]

The current status of hydrothermal liquefaction in the UK is TRL4 since it has only been validated in the laboratory environment [70]. A recent review has indicated that the technology is immature with scaled testing at a limited number of UK universities [97]. The University of Leeds, Imperial College and Bath University are the only known institutions actively involved in experimental research in this area [98, 99, 100]. A recent review from the University of Surrey suggested the research focus for the process [101]. It highlighted the developments needed in the field to allow for both wet and dry biomass to be processed through this technique. Currently challenged associated with the process is catalyst performance, efficiency, product quality and handling of the high volumes of wastewater. Stirring large volumes of biomass slurry at high pressure is problematic and the solid content needs to be less than 35% to ensure pumpability. The process remains expensive due to the components necessary to operate in a corrosive environment at high pressures. The technology is expected to reach TRL 8 by 2030 [70].

3.6. Summary of advantages and disadvantages of WtE processes

Looking at how prolific the processes are, HTL and AD lag behind incineration, gasification and pyrolysis in the UK, aligning with some of the issues discussed. Other process, such as fermentation, is used to some extent to produce bioethanol, but this is not so prevalent in waste feedstock streams. Incineration has been shown to be the most capable in feedstock admissions combined with the lowest end process waste percentages. However, this comes at the cost of lower efficiencies, high flue gas volumes and the loss of product extraction from the waste streams. The partial oxidations adopted in gasification and pyrolysis give advantages of lower flue gas volumes of which have lower percentage levels of oxidized species such as SO_X and NO_X, resulting in smaller flue gas treatment systems.

The other main advantage is the product extraction possibilities. Notably pyrolysis process results in products of higher energy density. Although not discussed, plasma pyrolysis and plasma gasification among others are some of the technological advances of these processes, essentially working at higher temperatures to create more reactions and result in less end process. AD is shown to be different from the other processes, attaining products without the need of high temperatures and complex systems. But AD is limited to predominately manure feedstocks and economic uncertainties through lowering levels of government schemes and grants. This is alarming, considering a degree of pollution raw manure is responsible for. HTL offers a pathway to obtaining bio crude oil which can be upgraded and refined to match petroleum-based fuels from waste streams, unlike other processes that use more valuable resources, such as rapeseed biodiesel, for instance.

One thing that has been made clear across literature of WtE processes is that although some of the processes have the ability to deal with a wide variety of wastes, the facilities are usually specifically designed to suit one particular waste stream. For example, in 2009 the chimney of ConTerm pyrolysis plant in Hamm Germany collapsed. The accident was the result of an insulation problem which lead to very high temperatures and softening of the steel structure. It was later found that inadequate sorting of the waste stream was a key contributor, as the feed characteristics exceeded the process design resulting in excessive temperatures past tolerable limits [7].

The utilisation of waste streams for energy and products has proven to be well documented, with landfills now considered as temporary storage. Waste FOG’s and food can be fully utilized for WtE processes, same goes for WWS. Despite the widespread implementation/capture of these wastes in the UK, it still requires a degree of work in achieving a circular economy as the government plans.

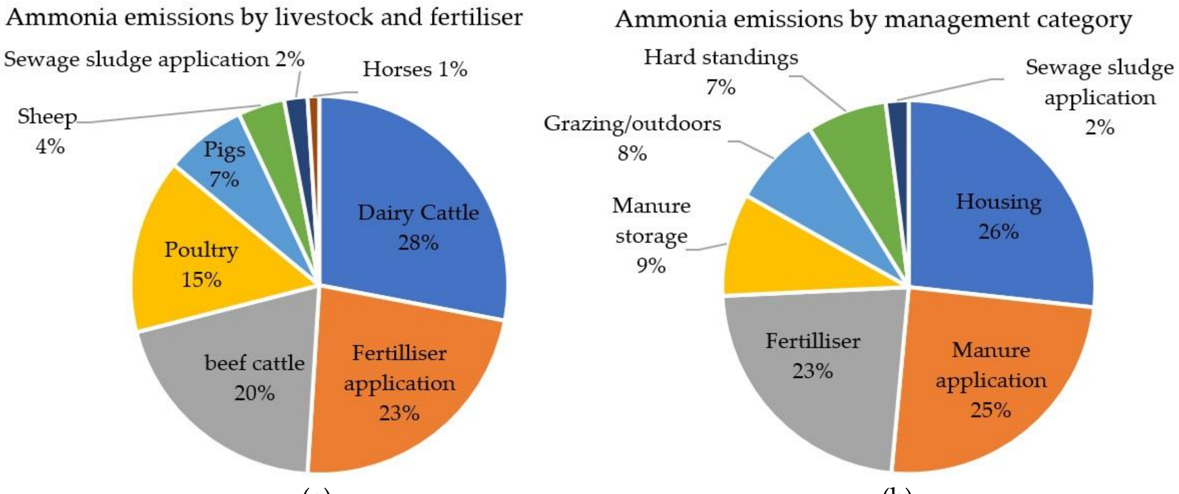
4. Discussion on the Effects of Manure and Barriers to Processing

When looking at preventative environmental emissions, manure as a feedstock remains largely untouched. As a result, high concentrations of NO_X, ammonia and methane, which are retained in the manure are emitted into the environment. A complete contrast is shown to strict legislation placed on internal combustion engines for NO_X emissions, which in fact, account for far less of the anthropogenic emissions than manure. These and other wastes discussed in the previous section should be the subject to a higher attention even if they are responsible for a lower fraction of the emissions of manure. Therefore, this section will cover the issues of manure and anaerobic digestion related to the environment, economics, legislature, and implementation. It will discuss the severity that untreated manure can pose in the UK through emissions of nitrous oxides, methane, and ammonia. Amount of emissions produced by manure can be mitigated through WtE processing by avoiding the barriers preventing the implementation of this as a whole, and also bringing most of manure generated in the UK under pollution control.

4.1. Environmental effect of emmisions from manure

4.1.1. Ammonia

Overall, the agricultural sector accounts for 88% of all NH_3 emissions in the UK and is estimated at 94% in the EU [101, 102]. The lack of manure and sludge treatment in the UK results in the livestock industry accounting for 66% of all ammonia emissions, as shown in Figure 4 (b) (not including grazing/outdoors), according to the Department for Environment Food and Rural Affairs (DEFRA) [102]. The figure related to manure and slurry production is not taking into account cattle graze on open fields for at least half a year, not counting some unavoidable proportion of ammonia (NH_3) emitted into the atmosphere. Report on NH_3 emissions produced by agriculture sector was prepared by DEFRA. Figure 4 (a) shows the proportion of ammonia emissions per livestock.



(a) (b)

Figure 4. Ammonia emissions within agriculture by (a) livestock and fertilizer category and (b) by agricultural management category [102]

An estimation from Figure 4 can be made on the true amount of NH_3 emissions, the direct result of manure formation and slurry at around 40 % (Manure storage 9% + Grazing 8% + Hard standings 7% + Sewage sludge 2%) of 66% of all ammonia emissions subject to unavoidable losses through animal grazing and hard standings. Hard standings are defined as unroofed paved or concrete areas. Examples include areas outside the milking parlor, where dairy cows congregate prior to milking. Meaning that up to 40% of NH_3 has the potential to be avoided with widespread waste to energy processes applied. This 40% in 2019 amounts to 86.2 kT of NH_3 emitted every year [103]. As NH_3 is a soluble alkaline gas with a high reactivity, the effects to the environment are numerous. In terms of the atmosphere, it reacts with acid pollutants such as the products of SO_2 and NOx emissions to produce fine ammonium NH_4+. Both forms have a lifetime of 10-100 years which lessen the overall effects atmospherically but creates localized affection zones with high concentrations of NH_3 and ammonium fallout [104]. The effects of ammonia vary as it is a commonly found naturally. One of the most notable aspects is the unpleasant odour, which even at low concentrations due to the pungency is still detectable. In the atmosphere, it can be an irritant to the eyes throat and lungs in high concentrations, the ammonium can penetrate deep into the lungs with links to respiratory problems and diseases due to the fine particle size [105].

For vegetation, ammonia is on the most part beneficial as a source of nitrogen essential for the formation of amino acids. When in the form of ammonium and is deposited onto soil it is converted by bacteria into nitrates which are then absorbed by roots increasing growing rates of nitrogen loving plants. But this can lead to imbalances affecting biodiversity, where nitrogen loving plants take over smothering out other species less effective in nitrogen take up. NH_3 pollution also effects species through soil acidification, damage to leaves through a burning effect reducing the resistance to frost, pathogens and drought. These negative effects in a report conducted by RAND [106] say that by 2020 the negative impacts could be equivalent to the cost of more than £700,000,000 per year.

The effects of NH_3 in water sources is notably more severe, with links to eutrophication and acidification, where in concentrations ranging from 0.53 to 22.8 mg/L it becomes toxic to freshwater organisms. The toxic effects differ depending on species but generally fish may suffer loss of equilibrium, hyper excitability, increased oxygen uptake and increased heartbeat rate. In extreme levels NH_3 can cause fish to suffer convulsions, coma and death. Even at levels below 0.1 mg/litre fish can experience irritation, gill damage, reduction in hatching and growth rates [107]. Fish and aquatic life can also be indirectly affected through eutrophication creating algal blooms reducing the amount dissolved oxygen.

4.1.2. Nitrous Oxides (NO_x)

This is another notable pollutant given off by manure, known for its high GWP of 298 times that of carbon dioxide. The lifetime is around 110 years in the atmosphere where the process that removes NO_x from the atmosphere contributes to depletion of the ozone layer [108]. Aside from methane and ammonia, NO_x is the 3rd biggest contributor in emissions from agriculture. The degree of NO_x produced from manure is dependent on the amount of aeration where the greater availability to oxygen leads to more NO_x formation. Looking back at the waste to energy processes, anaerobic digestion offers the most suitable option in limiting NO_x formation. The amount of NO_x emitted as the direct result of manure is unknown, however the overall NO_x emissions from agriculture are known to be 27 kT in 2017 [109]. This amounts to 3% of the total NO_x emissions in the UK, with transport contributing the most, 34%. Contradictory to this data, the national statistics for the UK in 2017 showed that in fact agriculture is responsible for 70% of NO_x emissions, amounting to 14.3 Mt CO_2e [110].. As both are from reputable governmental sources, this serves as an example of the degree of uncertainty these estimates are subject to. Nevertheless, more trust will be placed on the higher figures when looking at another report stating it to be 65% [111]. Similarly, to the NH_3 emissions, the amount emitted as the result of manure can be expected to be considerably less. 28% is a reasonable estimation if manure amounts to 40% of agriculture's overall impact.

4.1.3. Methane

As with nitrous oxides, methane presents a significant contribution to greenhouse gases with a GWP 25 times that of CO_2 and a lifetime in the atmosphere of around 10 years, where other chemicals in the air are responsible for its removal. The main source of methane is from the natural decomposition of organic matter in anaerobic conditions. As manure and slurry present large quantities of organic matter they contribute significantly to the agricultural sectors total emissions 51% of the UK's anthropogenic methane emissions in 2015 [112] and 50% in 2017 [110]. Figure 5 shows this in comparison to other sectors highlighting again that agriculture is the biggest contributor. Unlike NH_3 and NO_x emission where artificial fertilizer contributes heavily, methane is almost exclusively from manure, slurry and the animals' digestive systems. As the animals are known to be high contributors a ballpark estimation would be that 45% of methane emissions within agriculture are the direct result of manure and slurry. This in wider terms translates to 22.5% of total methane emissions in the UK.

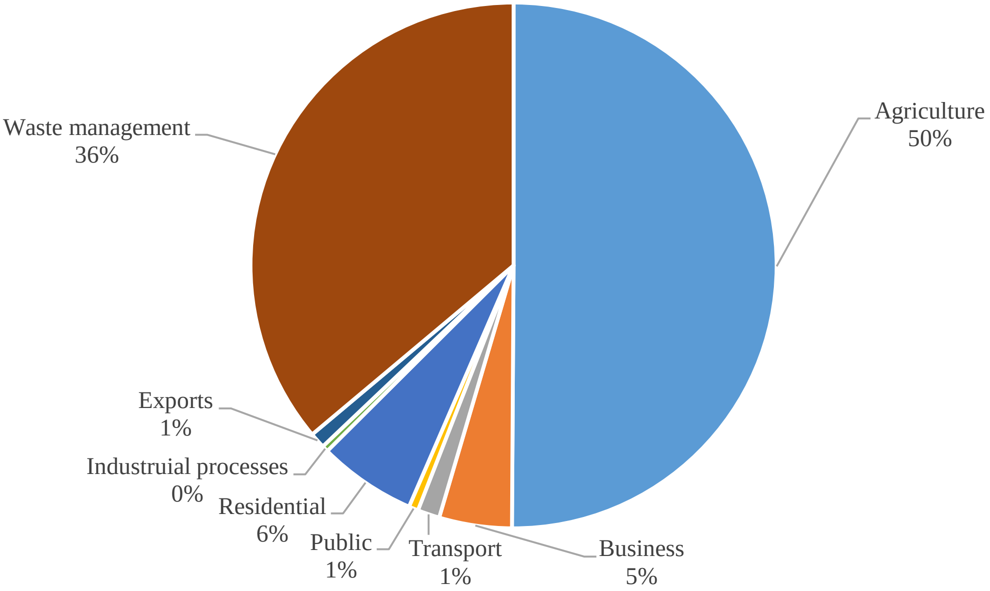


Figure 5. Methane emissions by sector in 2017 [110]

Methane can present an explosion risk at 5-15% content in the air [113]. There are numerous documented incidents where methane has been the result of gas fires and explosions in agriculture. For example, under certain conditions in which animals are fed a particular diet, this can result in the formation of bubbles containing methane in the slurry. The bubbles have been known to form a foam above the slurry which is susceptible to combustion [114].

4.1.4. Anaerobic digestion of manure as mitigation strategy for harmful emissions

The waste to energy conversion of manure to electricity, heat, fuel or grid gas is a four-stage process, as shown in Figure 6, consisting of hydrolysis, acidogenesis, acetogenesis and methanogenesis [115]. Manure feedstock is complex organic matter that consist of carbohydrates, proteins and fats. Through hydrolysis this is converted to soluble organic molecules such as sugars, amino acids and fatty acids. Acidogenesis or these components lead to the formation of volatile fatty acids, acetic acids, hydrogen and carbon dioxide. The volatile fatty acids is converted to acetic acids, hydrogen and carbon dioxide through acetogenesis. The last stage of the process is methanogenesis that forms biogas which can be converted into biomethane. Biogas is used at fuel in electricity and heating applications, while biomethane can be directed pumped into the national grid. Each stage the process is reliant on a number of microorganisms to participate in the reactions. Since this reaction occurs in an oxygen lean environment, there are less oxygen molecule to bind with the nitrogen molecules and form NOx.

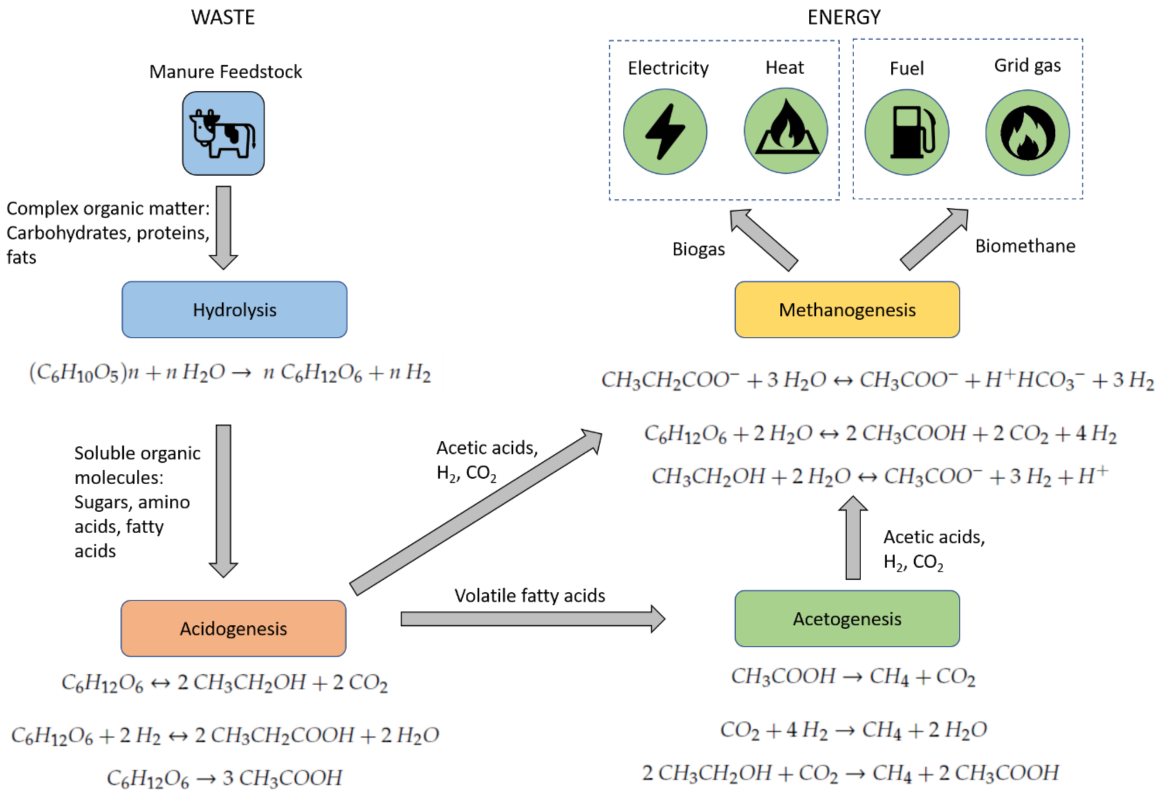


Figure 6. Waste-to Energy-process using manure as waste feedstock

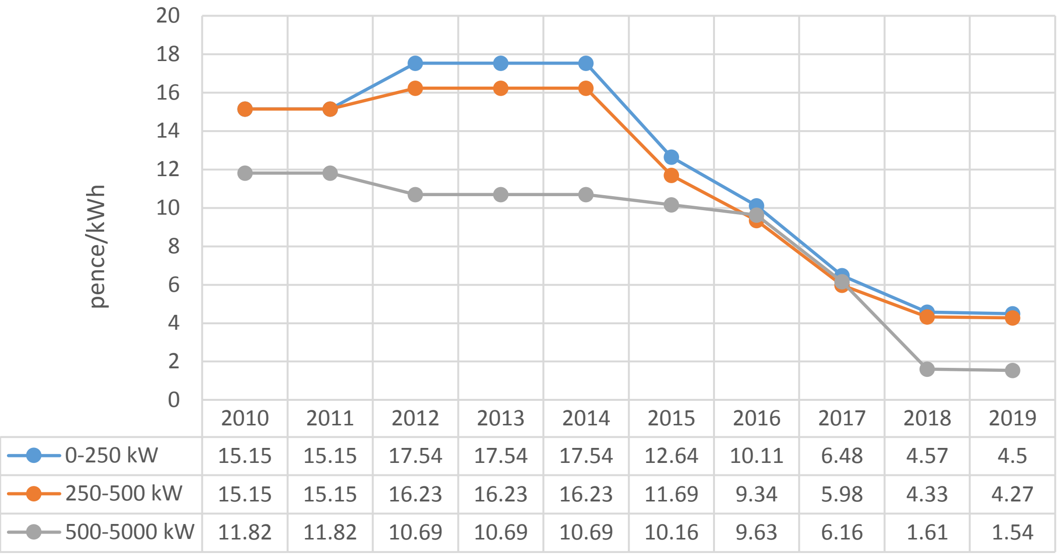
As highlighted, NOx formation is related to the degree of oxygen present when organic matter is decomposing, but when in an anaerobic environment, methane emissions increase. In the process of anaerobic digestion, this is ideal where the methane can be captured and used. In work produced by Sommer et al. [116], algorithms were developed for calculating methane and NOx emissions from manure management [116], in which, the degree of emission reduction through anaerobic digestion was calculated. The model predicted 90% reduction of methane from outside stores with digested slurry. The digested slurry/muck is said to have a reduction of more than 50% of NO_X emissions after the application of the digested slurry onto agricultural land vs that of untreated slurry. No estimations were made regarding the effect on NH_3 production, where this is considered an anaerobic digestion inhibitor, through the change in pH. High toxicity levels also destroy microbes that produce methane [117].

For reduction in NH_3 emissions, it is clear that anaerobic digestion is not best suited to this. The addition of magnesium ammonium phosphate otherwise known as struvite is said to reduce NH_3 levels in a digester. Where struvite is a valuable plant nutrient source that slowly releases nitrogen and phosphorus overtime, it also known for its low solubility in water. Uludag-Demirer et al. [118] in an experiment added a set amount of struvite to a digester, resulting in 11% NH_3 reduction. Other work in this area also highlights the role pH plays, highlighting reactor conditions having a significant impact. Apart from optimizing reactor conditions and introducing additives, further processing would be the next cause of action. The anammox process is one such process aimed at post digested effluent. It is considered an efficient biological method for nitrogen removal through ammonium oxidization to nitrogen gas in anaerobic environment. Molinuevo's experiments [119] found that up to 92% of ammonium could be removed this way. As it can be quite costly to remove the NH_3, others look towards how the manure is applied to soil and if emission mitigation can be achieved there. Some of the main techniques from this aim towards limiting the mixing the slurry and muck have with the atmosphere through trail hoses and direct injection. The trail hoses limit the surface area that the muck and slurry is applied to. From Sommer and Hutchings [120], this is said to reduce the amount of emitted ammonia by 40%. For injection, this figure is said to be even higher at 60% when in combination of harrowing prior to the application.

4.2. Economical aspects of anaerobic digestion

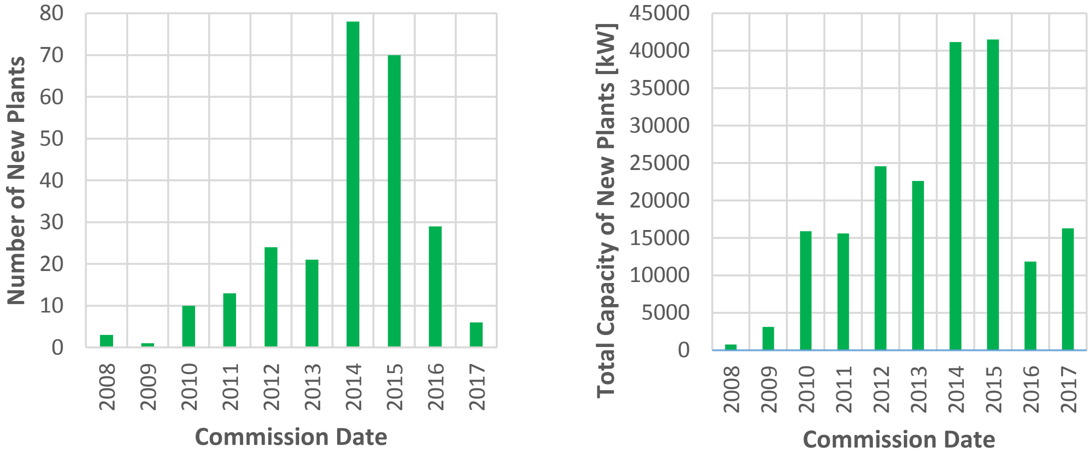
4.2.1. Current Incentives

As mentioned in the AD description, incentives have been on the decline at current, it can be assumed that almost all grants have been withdrawn by the government. Similarly, the tariffs in recent years have been reduced from 15.15 pence/kWh in 2010 to 4.50 pence/kWh in Jan 2019 for biodigester units less than 500 kW [121]. The gradual change in tariff rates for all sizes of AD is shown in Figure 7, offering a depiction of the decrease in the amount of government funds made available per year. The curves show the tariffs in pence/kWh for three bands of installed capacity: 0-250 kW, 250-500 kW and 500-5000 kW. Some studies suggest that such change in tariff rates is too high for average size of UK farms and that lower boundaries should be introduced. Even incorporating the sale price tariffs, the cost viability particularly for small scale farm systems comes into question. This can be linked with the step decline seen in the number of AD plants commissioned each year. Where from the peak of 79 new plants commissioned in 2014 a fraction of that number is now commissioned which was only 6 in 2017 [122]. This is shown in a graph taken from Savills summary [123] on AD growth and performance depicted by Figure 8. A clear link can be seen between the drops in tariff rates from 2014 to 2015 shown in Figure 7 to the fall in plants commissioned per year shown in Figure 8.



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
0-250 kW	15.15	15.15	17.54	17.54	17.54	12.64	10.11	6.48	4.57	4.5
250-500 kW	15.15	15.15	16.23	16.23	16.23	11.69	9.34	5.98	4.33	4.27
500-5000 kW	11.82	11.82	10.69	10.69	10.69	10.16	9.63	6.16	1.61	1.54

Figure 7. Change in generation tariff rate for anaerobic digestion [121]



(a) (b)

Figure 8. (a) number of AD plants commissioned from 2008 to 2017 in UK and (b) the total capacity of these plants in kW [123]

The numbers are very low considering the number of farms in the UK and goals set out by the DEFRA and National Farmers Union (NFU) aiming for 1000 on-farm AD plants by 2020 [124]. The actual number by 2020 will be considerably less highlighting the lag that this industry has to overcome if it were to pose a significant reduction in GHG emissions and averted emissions through methane capture pathways.

4.2.2. Capital Grants and Finance

The lag on the farm scale can be mostly put down to the capital costs required for installation. Almost all AD plants surveyed has some form of capital subsidy at 93% according to Bywater [90]. This is in part due to the financial status of smaller farms which can struggle to break even relaying on receiving farm payments from the government every year, making it unlikely that the capital would be available for such an investment. This lack of capital changes the use pathway of the methane gas, where expensive onsite gas cleaning and combustion in gas engines is not an option. Thus, the gas produced is merely used in boilers to heat farmhouses and to use for hot water, losing the potential for self-electricity generation and associated benefits. It is also worth noting that the tariff system changes onto the renewable heat incentive (RHI) as a result. A system not designed for this sector is providing yet a smaller insignificant income. Currently for small biogas combustion of which this pathway would fall under, the rate stands at 4.74 pence/kWh as shown in Table 10, further lowering the economic prospects for farm AD.

Table 10. Tariff rates for RHI (small biogas combustion) [125]

Eligible Technology	Eligible Sizes	Accreditation Date	Tariff Rate 2019/20 (pence/kWh)
Small Biogas Combustion	Less than 200 kWth	Before 1 April 2016	8.44
		Between 1 April and 30 June 2016	7.41
		Between 1 July and 30 September 2016	6.30
		Between 1 October and 31 December 2016	4.74
		Between 1 January and 31 March 2017	3.54
		Between 1 April and 30 June 2017	3.37
		Between 1 July 2017 and 21 May 2018	3.03
		On or after 22 May 2018	4.74

4.2.3. Supply of slurry and muck

There is a high volume of slurry and muck produced on farms, where for instance, a pig unit near York with around 5000 pigs produces 20m^3 of slurry a day and over 1000 tonnes of muck each year. More can be said of the future with farm operations switching to fewer much larger operations, as small holdings with less than a couple hundred acers struggle financially with expensive farm machinery required to operate and the lack of land and livestock to spread overheads over. It is said that in the UK, 4.5 times as much derived organic matter is produced from farm operations (including slurry and muck) as from food, 90 million tonnes compared to 20 million tonnes [90]. Thus, the supply is not an issue.

4.3. Legislation controlling implementation of anaerobic digestion plants

4.3.1. Environmental Permitting

This is the primary means of regulating and minimizing the impact business activities have towards all environment aspects for England and Wales, such as to the air, water, land and considering factors like noise and safety. For AD plants to operate and spread digestate, a permit must be obtained. This involves completing a technical application form, demonstrating competency and willingness to abiding by the conditions of the proposed permit. Currently this can be achieved through Charted Institution of Wastes Management / Waste Management Industry Training and Advisory Board (CIWM/WAMITAB) scheme or Environmental Services Association / Energy and Utility (ESA/EU) sector skills. Setting out 3 different types of permits as shown in Table 11.

Table 11. Anaerobic digestion permits

Type	Description	Conditions
Exemption	For small scale plants which aren't waste facilities	• Must provide technical information to the environment agency and register • No charges • Only for agricultural businesses and burning of resultant biogas at the site. • 1,250 m^3 limit for the total amount of untreated and treated waste on site at any time • 0.4 MW limit for the thermal generating capacity of the plant • Minimum 28 days residence time of the waste [126]
Standard	For plants which can operate within a set of standardised rules and conditions.	• AD processing facility including the use of the biogas • 100 t processing limit per day • Combustion of biogas can be in gas engines, boilers, turbines, fuel cells or upgrading to bio methane [127]
Bespoke	For plants that cannot adhere to all pre-defined rules or conditions	The conditions vary considerably where both stationary and mobile AD plants are categorised for in this type. However, the flexibility of this type comes at more cost and time. Details can be found on the government website [128].

4.3.2. Permits for Spreading Digestate

As with exceptions to environmental permitting, digestate that is solely from agricultural waste streams is exempted from disposal charges provided that a number of conditions are met. These are:

- Only can be spread on agricultural land
- 50 t per hectare spreading limit
- 200 t storage limit at any one time
- Digestate must be from waste streams that improve or maintain the physical, chemical and biological properties of the soil to grow crops [129]

Note that material that has reached PAS 110 and Quality Protocol standards is no longer regarded as a waste. As such, the restrictions above no longer apply.

To spread waste material which does not meet the publicly available specification (PAS) 110 for agricultural and non-agricultural land for business or environmental enrichment, a permit is required. That is if the spreading activities to agricultural land exceed the exception conditions. Generally, a standard rule permit is given with the conditions and charges depicted in the government publication "SR2010 No.4: Mobile plant for land spreading" which specifies:

- A 250 t per hectare spreading limit
- 3,000 t limit for the amount of waste material on site at any time
- 12-month storage limit for the material
- For every spreading application of material to the land a charge must be payed depending on material type and the risk it poses, ranging from low, medium and high

High risk (Category 2) animal by-products (ABPs) cannot be used as feedstock in AD plants, unless they have been treated to a 133°C/3 bar/20-minute EU pressure-rendering standards [130]. Contrary to this manure is classified as a category 2 ABP, however, manure can be used without processing as raw material in an AD plant. But when mixed with ABPs such as catering waste the mixture must be rendered to the heat and pressure regulations prior to anaerobic digestion.

4.3.3. Planning Permission

Potential issues surrounding planning of AD plants revolve around 5 main concerns as highlighted from the governments planning policy statements and supplementary planning guidance [131]. These are:

Site Selection. The AD reactor tank can sometimes be quite large presenting a significant change to a landscape, where tanks can reach as high as 15 m. However small on farm digesters can sometimes be accommodated within the farmyard and buildings concealing it to an extent. Where this may not be possible, in the interest of reducing tank visibility, it can be somewhat burried in the ground reducing the visual impact. The burial also offers heat insulation benefits. Centralised AD plants have issue of the transport of feedstock involved, affecting chances of approval, giving on-farm plants the advantage.

Feed Stocks and Product Storage. Planning permission may be given only for specific feedstock, adding to or changing the feedstock is not allowed without further planning consent. This ties in with the exception permit given to farms that by adding other feed stocks it can lead to the exception being revoked. The storage of slurry and muck used in on-farm AD plants is covered by the water resources (control of pollution) (silage, slurry and agricultural fuel oil) England regulations and the nitrates directive (91 / 676 /EEC). Specifying the minimum standards for construction related to the design and operation of any farm slurry storage system.

Odour. AD by its nature of breaking down organic matter is an odorous process, this is of concern. Where predicted odour effects and proposed mitigating measures should be reviewed. If a location is considered to be sensitive to odours, information on the control measures should be provided from the developer to ensure that all sources are accounted for. Farms are already known for to be odorous and thus odour concerns are lessened to those of centralized facilities.

Emissions to Ground and Water Courses. As has been made clear in previous section, the runoff from raw agricultural wastes such as manure and slurry can contribute to serious farm pollution incidents. Therefore, the AD of farm waste should be conducted in a manor to reduce the likelihood and ability of the material to pollute water sources. In many application cases, the requirement of a bound wall is put forward by the planning authorities to prevent effluent spillage in the event of a leak. As for ground water leaking, the surround surface of a supposed plant is usually required to be concreted and run off prevented from reaching normal drains. Delays in the planning process can be the result of concerns in regard to designs inadequacies.

Emissions to Air. The production of biogas from AD and its uses contributes to a number of emissions to the atmosphere, manly from engine exhausts, gas vents and flare stacks. The emissions can however be considered insignificant provided the equipment meets design specifications and is routinely serviced. For larger on-farm and centralised AD plants integrated pollution control measures are required to control the emissions to meet regulations.

4.4. Implementation of anaerobic digestion to farms

4.4.1. Slurry and Manure as a Feedstock

Without adding other feedstock, the AD of slurry and manure has been proven to be uneconomical for both on farm and centralized plants due to the low gas yields, high capital cost and absence of gate fee. The legislation also plays a large role here in the restrictions placed on the exception type permit for farm-based plants. Other wastes such as those from grain processing can be added to increase gas yield without increasing the potential environment effects. In surveys conducted in 2017, it was reported that there were 401 AD plants in the UK, if those for treating sewage sludge are ignored, with more than half at 221 utilizing slurry and manure as feedstock. However, those dedicated to only slurry and manure are uncommon making up just 6% equating to 24 plants, with the capacity of processing 165,000 tonnes per year [132].

4.4.2. Grid Connection Issues

For widespread implementation of AD to farms, significant issues can be expected in connecting to the grid in part due to the low load electricity lines supplying many farms and the power of transformer. If the national grid deems the transformer inadequate, this can make the implementation of an AD plant to produce electricity not economically viable. Because it is presumed that small AD plants are unlikely to produce significant extra electricity that can be sold to the grid.

4.4.3. Lack of Land

From the regulations on digestate spreading where 50 tonnes per hectare is the spreading limit, large livestock farms particularly those where the animals are kept indoors all year round and have little in terms of land can be a significant issue. On the contrary these farms must find ways to get rid of slurry and muck like the straw-muck exchange highlighted in the feedstock preliminary section. And if this were to be replaced by digestate the application rates are the same. If PAS 110 and Quality Protocol standards are achievable, converting slurry and manure to digestate would be very advantageous for surpassing the application limits.

4.4.4. Technology

If widespread implementation were possible this could see a significant contribution to the UK's energy demands if the majority of manure and slurry were to be processed. This amounts to 90-100 million tonnes of agricultural by-products such as manure and slurry available each year in the UK. This is based on a 20 m^3/t (8% dry matter) average gas yield of slurry, that 1.7 kWh of electricity is produced per $1m^3$ of gas due to conversion losses and if 50% of the available manure/slurry can be processed, 1.615 TWh worth of electricity could be produced. A reasonable estimation which could provide 0.45% of the UK's annual demand, based on 2018 at 352.064 TWh [133]. A low percentage, but after considerations of the useful heat that can be harvested alongside the emission mitigations, it becomes more considerable. But the low electricity generation is a limiting factor in the technology potential.

4.4.5. Operation

The success of an on-farm AD plant, no matter how good the design nor technology, is inevitably comes down to operator skills, frequent monitoring and feeding the digester. On many farms, the muck and slurry are required to be mixed into the digester at a certain ratio for instance. Adding to this AD's can be plagued by a number of problems namely:

- Frothing
- Acidification
- Increasing viscosity
- Increasing volatile fatty acids (VFA) and total inorganic carbon (TIC) value
- Poor methane yield

These problems, if not corrected and kept on top off, can lead to poor biogas yield. Frothing alone can reduce biogas yield by up to 20% [134], with the cause linked to the constitution of the digestant and mixing routines within the reactor tank. These problems make time allocation and training a must for the farmer/operator. As such, a best practice guide should be made available if not already on the operation of AD plants specific to slurry and manure.

4.4.6. Bespoke cases

One size does not fit all in the case of widespread farm implementation, every farm is individual and presents its own challenges. The differences from farm to farm can be enormous from the amount of slurry and muck produced, to the characteristics of the feedstock and the planning complications. At a government level to seek to drastically increase the number of on-farm AD plants, this would prove complex as what may be beneficial to one may be inadequate to another.

Here, we provide two cases of commissioning of anaerobic digesters, which use manure as a feedstock. The first case is the Copys Green Farm located in Wighton, Wells-next-the-Sea in the eastern part of the UK, as shown in Table 12. The farm is very much sustainability driven and owners won a number of awards for doing so, namely the Farmers' Weekly green energy farmer of the year 2010. Note that £100,000 grant from bioenergy was turned down due to stopping double Renewable Obligation Certificate / Feed-in Tariff (ROCs/FIT) from being revived. Payback period was estimated at 8 years with a £83,000/year running cost most of which was the high energy feedstock. The biogas was produced at the rate of 70 m^3/hr burned to generate 131 KVA for grid export. In the planning and development stage the biggest barriers to on-farm AD is described as administrative. This includes the environment agency and OFGEM paperwork, where the owner feels the paperwork is disproportionate to the risk.

Table 12. Summarised data of Copys Green Farm [90]

Digester Size	870 m^3 (mid to large size)
Digester Type	Mesophilic, insulated, steel glass coasted tank with fixed roof
Gas Use	140 kW CHP, Feed in tariffs, extra heat used in grain drying, cheese making, dairy hot water and heating the farmhouse.
Commissioned	2009
Feedstock (tonnes per year)	Slurry from 100 dairy cows estimated at 2,500T/yr, Maize Silage or fodder beet estimated at 2,500T/yr, Whey from cheese making supposed feed stock to be incorporated but not yet would be around 210T/yr
Farm Size	230ha, arable and dairy, all in NVZ (Nitrate Vulnerable Zone)
Capital cost	Estimated to be £750,000, self-financed, with £100,000 capital grant turned down.
Issues	Unreliability of CHP. Tech provider issues (takeover midway through project)
Barriers to AD	Administrative: EA and OFGEM paperwork
Advantages	Recycling and improved utilisation of crop nutrients. Reducing risks the manures pose to NVZ area as digestate

The second case is a Woodhead farm located near Annan in Dumfries and Galloway in the western part of the UK, as shown in Table 13. A SlurryGen-50 digester was installed by Advanced Anaerobics Ltd. to help reduce electric bill and generate income [135]. 500 kWh is used each day of the total 1,200 kWh produced with the balance exported to the grid. Owners applied for the feed in tariff in 2014 securing 12.46 pence/kWh. The excess heat is planned to be used on farm and generate additional income through RHI scheme. With these tariffs and savings to the electricity bill, payback period is estimated 60 months (5 years). It is said that for each ton of dry organic matter in slurry can produce 300-400 m^3 of biogas. Operating cost is highlighted as an issue in this case study, because for example the CHP generator requires routine maintenance and periodic engine rebuilds. Over a 20-year lifetime, the operating costs of the plant as a whole will exceed the initial capital cost.

The Farmers' Weekly points out that in 2015 only 18 slurry AD plants were running in the UK. There were however 20-30 units at the planning stage. More widely 280 on-farm plants have been encouraged with RHI and FIT's.

Table 13. Summarised data of Woodhead farm [135]

Digester Size	Small
Digester Type	Mesophilic, insulated, steel glass coasted tank with fixed roof

Gas Use	50 kW CHP, some used on farm, rest exported to grid through feed-in tariff. Surplus heat planned to be used on farm under RHI
Commissioned	2015
Feedstock (tonnes per year)	Slurry from 320 dairy cows estimated at 24 T/day
Farm Size	n/a
Capital cost	Estimated to be £400,000 (self-financed)
Issues	Operating cost due to small plant
Barriers to AD	Administrative: EA and OFGEM paperwork
Advantages	Smaller size, simplified planning and permits, as does not need crop or other material brought in, there is no requirement to qualify as consented waste management site and lower capital cost.

4.5. Summary of manure and AD implementation

Manure and slurry present significant anthropogenic emissions of NH_3, NO_X and methane in the UK at 40%, 28% and 22.5% respectively. This requires that anaerobic digestion mitigations of 90% in methane from stores and 50% in NO_X emission after the application to land can be achieved. However, AD has poor NH_3 reduction capabilities, requiring extra processing. Although a more effective migration pathway may be to change how muck and slurry are applied to land, a reduction of up to 40% is achievable by minimizing aeration.

Sharp drops in tariff rates, high capital requirements and lack of grants make the economic side of AD an issue. On-farm AD has been named numerously as the most suitable type for manure but the least viable. Therefore, reforms to the incentives are a must if the number of AD plants are to increase in the UK, especially on-farm types which rely on grants. As the current tariff banding system is unsuitable for on-farm AD, implementing higher paying bands would be advised. A gate fee for processing, which includes the cost of opening, maintaining and eventually closing the site and also may include taxes applicable in a region, would also be advised to reduce dependence on biogas yield and temptations of using high energy crops.

Legislation and planning play a key role in the establishment of farm digesters with exception permits designed for this scenario, but for an exception to be grated strict rules apply. For more normal or unique operations, two other permit types (a standard rule permit SR2010 and a planning permit) can be granted at a cost and more time. The quality of the digestate is key in what can be done with it and how much can be applied to agricultural land. For use on non-agricultural land digestate incurres charges, limitations of quality and permitting (if still a waste). Manure is also found to be categorized as a high-risk waste which presents pressure and heat rendering incursions. These can however be ignored provided it is not mixed with other animal by-products. Overall, the legislation can be said to be well founded and necessary. Planning permission for many is where issues arise in legislation delaying a project or preventing its construction. The case studies show legislation is a barrier to AD. But as the planning difficulties are routed in reducing the risk an AD plant poses to the surrounding environment, no changes are envisaged as to ease the implementation of wide spread AD plants, with the environment as one of the primary focuses of this paper.

A significant amount of electricity could be produced, at 1.615 TWh equivalent to 0.45% of total UK's annual demand. Potential grid connection issues can limit this but for small on-farm plants encouraged in this report it can be said to be minimal, with the majority of the useful energy used onsite. Furthermore, the bespoke requirements for on-farm AD are known to present difficulties for the widespread implementation. Finally, as stated, inevitably the success of an AD plant comes down to operation. Improper monitoring and lack of know-how can lead to poor gas yields through problems common to digesters. Therefore, training and courses on operation are a must not just to prove competency for attaining permits but also for good operating practice.

5. Conclusions

Waste-to-energy sector is well developed with a number of processes capable of dealing with a variety of waste streams for energy and product extraction, improving sustainability and waste management, critically displacing fossil fuels and transferring towards a circular economy. However, challenges remain in the effective implementation of these processes in the UK. From the existing body of studies, it is clear that no 'quick fix solution' will guarantee energy sector decarbonisation. Conventional bioenergy's capacity to produce significant GHG reductions is being constantly debated. Sustainable residues and waste from biomass may and should definitely be part of this solution. This review has focused on certain waste streams such as biomass residue and agricultural waste, landfill waste, food waste, fats-oils-grease, wastewater sludge and manure, because they are considered potentially sustainable feedstocks. With a broad variety of current applications for several of these feedstocks, it will require strong environmental protections to avoid harmful environmental and social outcomes. Although the amount of such waste materials will be raised, it will decrease for certain wastes. Given the importance of several other applications, only a portion of the future flow of such resources can be devoted to the development of bioenergy. Of this among other purposes, there is substantial confusion regarding the exact quantities among energy values of the feedstocks that could be used sustainably of bioenergy development in the UK and further research on this is desperately required, taking into account economic forces, competitive applications, environmental imperatives and other considerations.

90 million tonnes of manure and slurry in the UK remain largely untapped, presenting the biggest contributions to ammonia, methane and nitrogen oxide anthropogenic emissions of any other waste or industry in the UK at 40%, 22.5% and 28% respectively. With large scale implementation for on-farm AD, mitigations for 90% and 50% of methane and nitrogen oxide could be achieved with the added potential of generating more than 1.615 TWh of sustainable electricity. Further processing and changing application methods of slurry and muck to land is required to reduce ammonia emissions. Barriers in the form of insufficiently high banding and tariff systems, planning, high capital costs, lack of government subsidies and low gas yields prevent this. Therefore, it would be suggested that a lower high paying tariff banding system needs to be introduced to increase AD plants on farms. It is suggested an addition of a gate fee payment to reduce high energy crops used as supplements for gas yield, and to increase the amount of slurry and muck that are digested. The bespoke nature of farms could still present a fundamental issue in the degree manure and muck in the UK are processed.

The use of biomass capital to decarbonize the UK energy market has considerable potential, and the use of sustainable biomass waste and residues can be part of this solution, both in the direct processing of liquid and gaseous fuels as well as in the supply of renewable electricity generation capacity to decarbonize the UK grid and (indirectly) power a possible fleet of electric cars. Fostering the use of wastes and residues to create jobs in the UK also has considerable value. This is especially true for the AD industry where anaerobic digesters are widely distributed throughout the country, including in rural areas. There is also a need for the UK Government to step up measures to ensure efficient waste and residue production and we recommend a combination of responses including:

- Supporting effective EU policy reforms to promote a transition from traditional energy to sufficient advanced bioenergy from waste and residues;
- Formulating specific protections to follow the usage of waste and residues in the energy and transport field, notably in the absence of protections established at EU level as part of the existing Renewable Energy Directive adjustment procedure. A crucial precaution is the development of the required carbon accounting system for waste and residues, taking proper account of shifts in soil carbon supplies (e.g. in relation to straw extraction). The design of these protections will profit from cross-departmental collaboration to insure, in particular, that waste management priorities are not undermined;

- Research commissioning to enhance the perception of target applications for waste and pollutants, taking into consideration the business condition in the United Kingdom with regard to domestically accessible production and current applications (energy and non-energy). This would also create more accurate figures of the quantity of waste and contaminants that may be applicable to the energy and transport industry. Although we have established the feedstocks that currently tend to be more renewable, their processing into biofuels or biomethane might not be the more 'sustainable' usage, for example in terms of the total GHG emissions avoided;
- Cross-sectoral guidance on encouraging safe management and handling of waste and residues. Cooperation amongst policy departments collaborating on sectoral policies (agriculture, forestry, waste) and establishing targets for green energy and transport policies is required to ensure that policies in various sectors are complementary. It will result in valuable guidance to the various sectors and stakeholders and cause collaboration between, for example, producers, forest owners, waste processors and bioenergy or AD plant operators;
- Providing funding resources to develop emerging waste-to-energy processing technology. It would possibly involve capital funding for new projects, as well as help for current infrastructure growth. This would help increasing the potential of waste-to-energy processing and enjoy the advantages of technical innovation to reduce the costs of emerging technology.

Initiatives in these directions would be required not only to promote the development of an innovative waste-to - energy sector, but also to establish an acceptable route for the wider usage of bioenergy and biomass. There is an ability to reap several benefits by producing more green electricity, improving engineering know-how, and creating economic benefits like a large amount of potential jobs by turning waste and residue currently underutilised into beneficial uses. If protections are introduced, the environmental advantages of switching away from traditional biofuels in decarbonizing the UK energy and transport market would improve.

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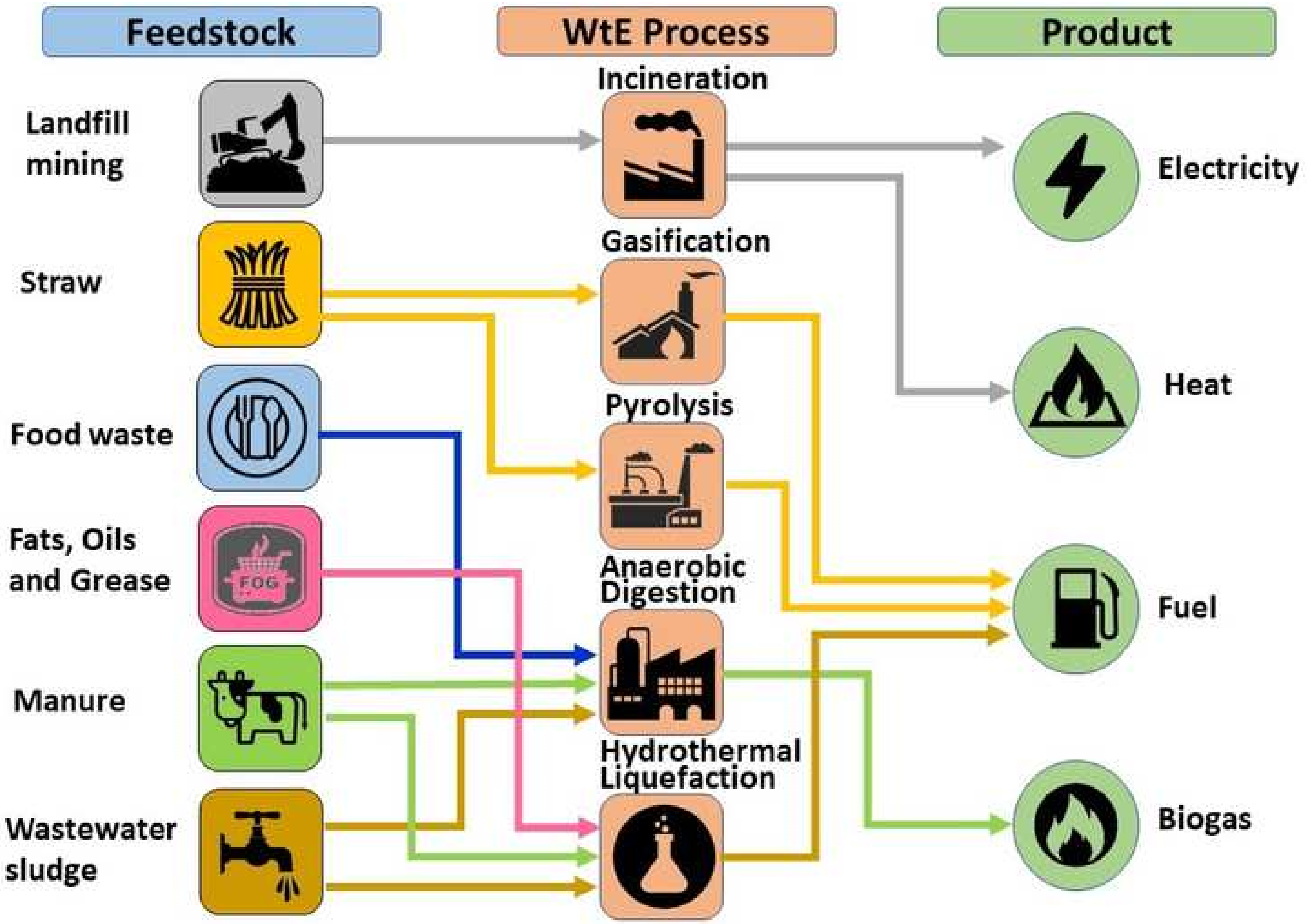
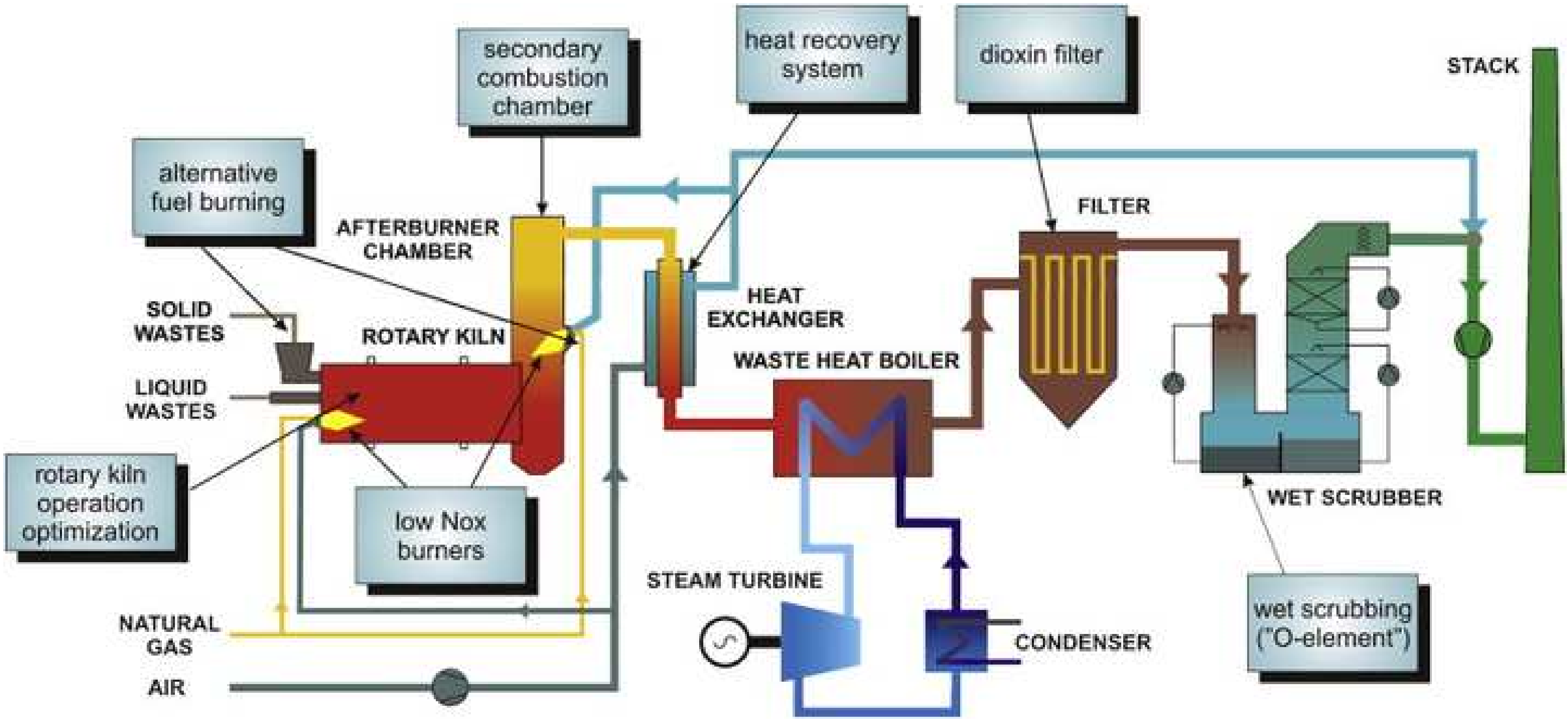
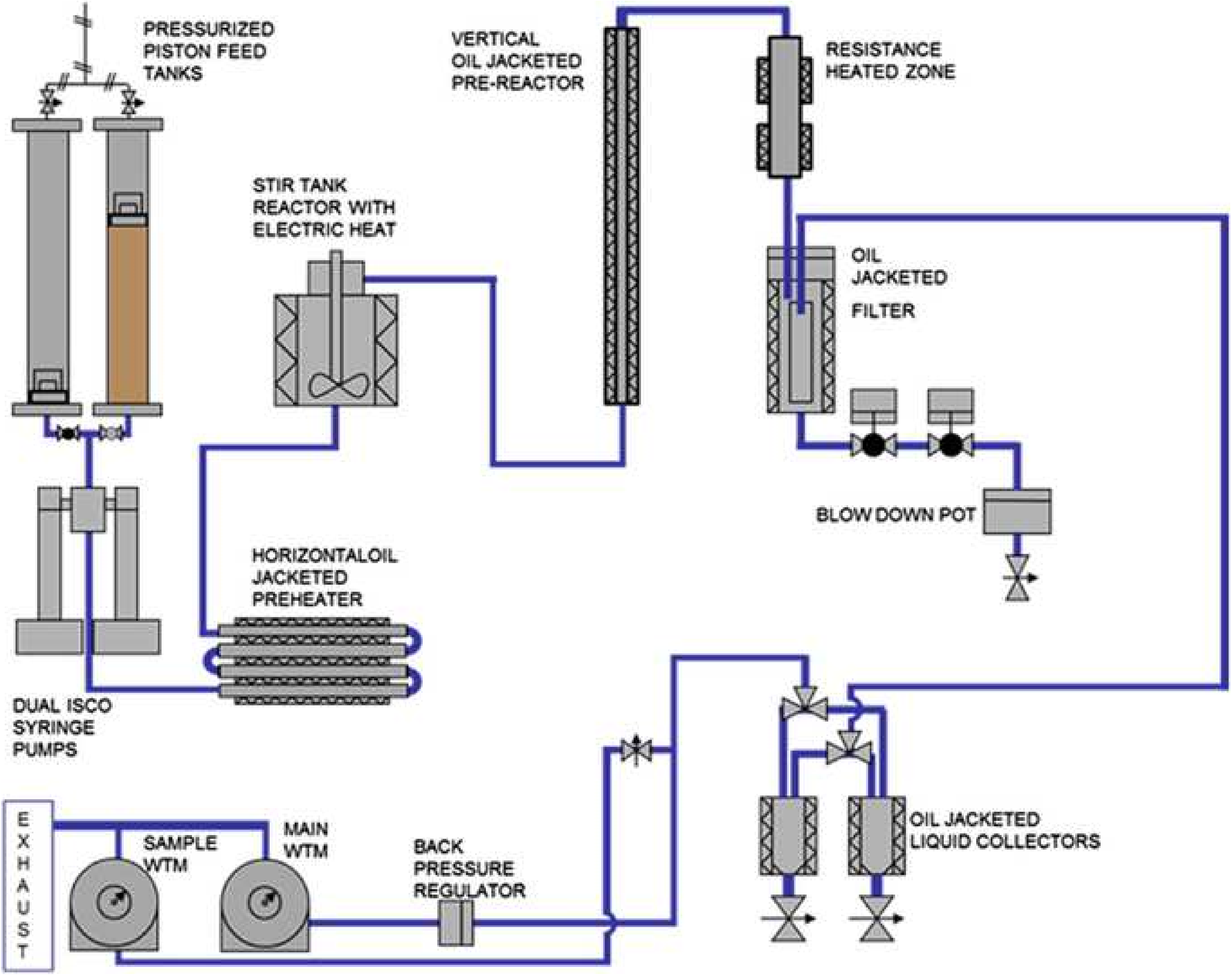
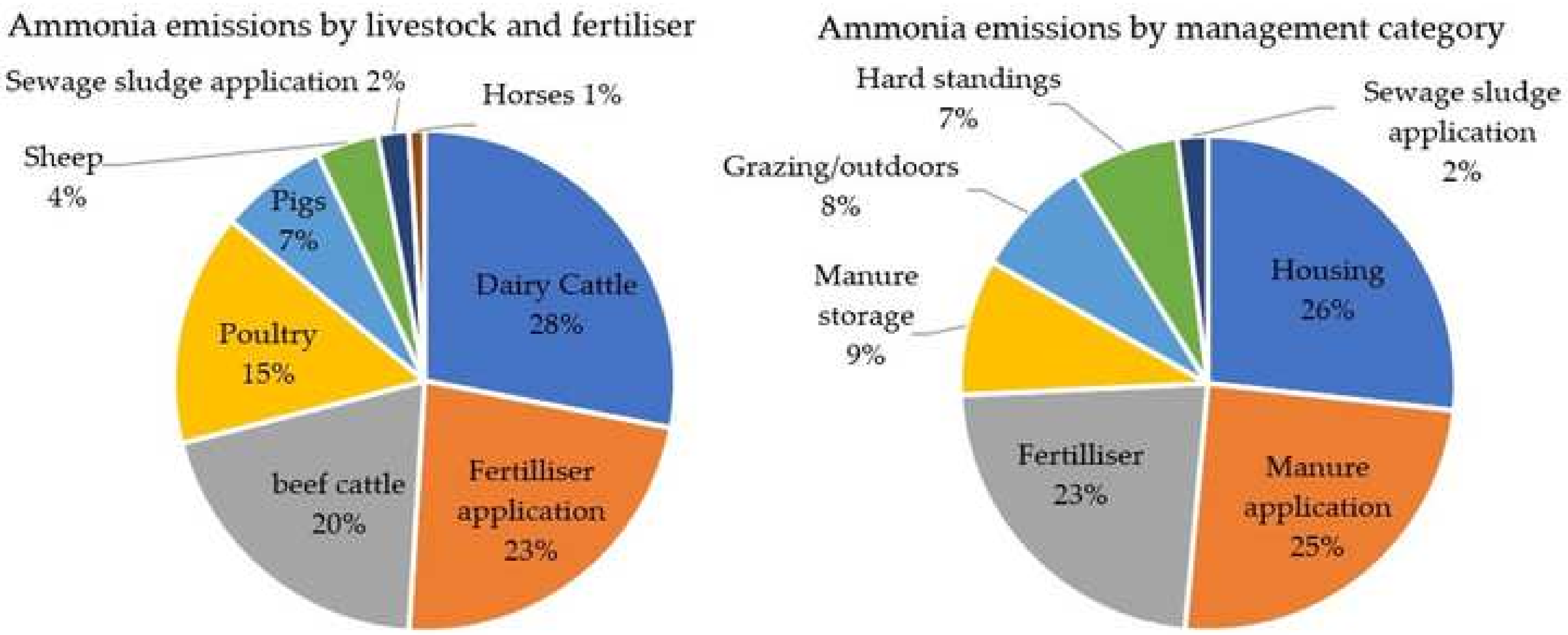
Figure 1


Feedstock
WtE Process
Product
Landfill mining
Straw
Food waste
Fats, Oils and Grease
FOG
Manure
Wastewater sludge
Incineration
Gasification
Pyrolysis
Anaerobic Digestion
Hydrothermal Liquefaction
Electricity
Heat
Fuel
Biogas


secondary combustion chamber
heat recovery system
dioxin filter
STACK
alternative fuel burning
AFTERBURNER CHAMBER
FILTER
HEAT EXCHANGER
SOLID WASTES
ROTARY KILN
WASTE HEAT BOILER
LIQUID WASTES
rotary kiln operation optimization
low Nox burners
WET SCRUBBER
STEAM TURBINE
NATURAL GAS
CONDENSER
wet scrubbing ("O-element")
AIR


PRESSURIZED PISTON FEED TANKS
VERTICAL OIL JACKETED PRE-REACTOR
RESISTANCE HEATED ZONE
STIR TANK REACTOR WITH ELECTRIC HEAT
OIL JACKETED FILTER
BLOW DOWN POT
HORIZONTALOIL JACKETED PREHEATER
DUAL ISCO SYRINGE PUMPS
EXHAUST
SAMPLE WTM
MAIN WTM
BACK PRESSURE REGULATOR
OIL JACKETED LIQUID COLLECTORS

Click here to access/download;Figure;Figure 4.jpg



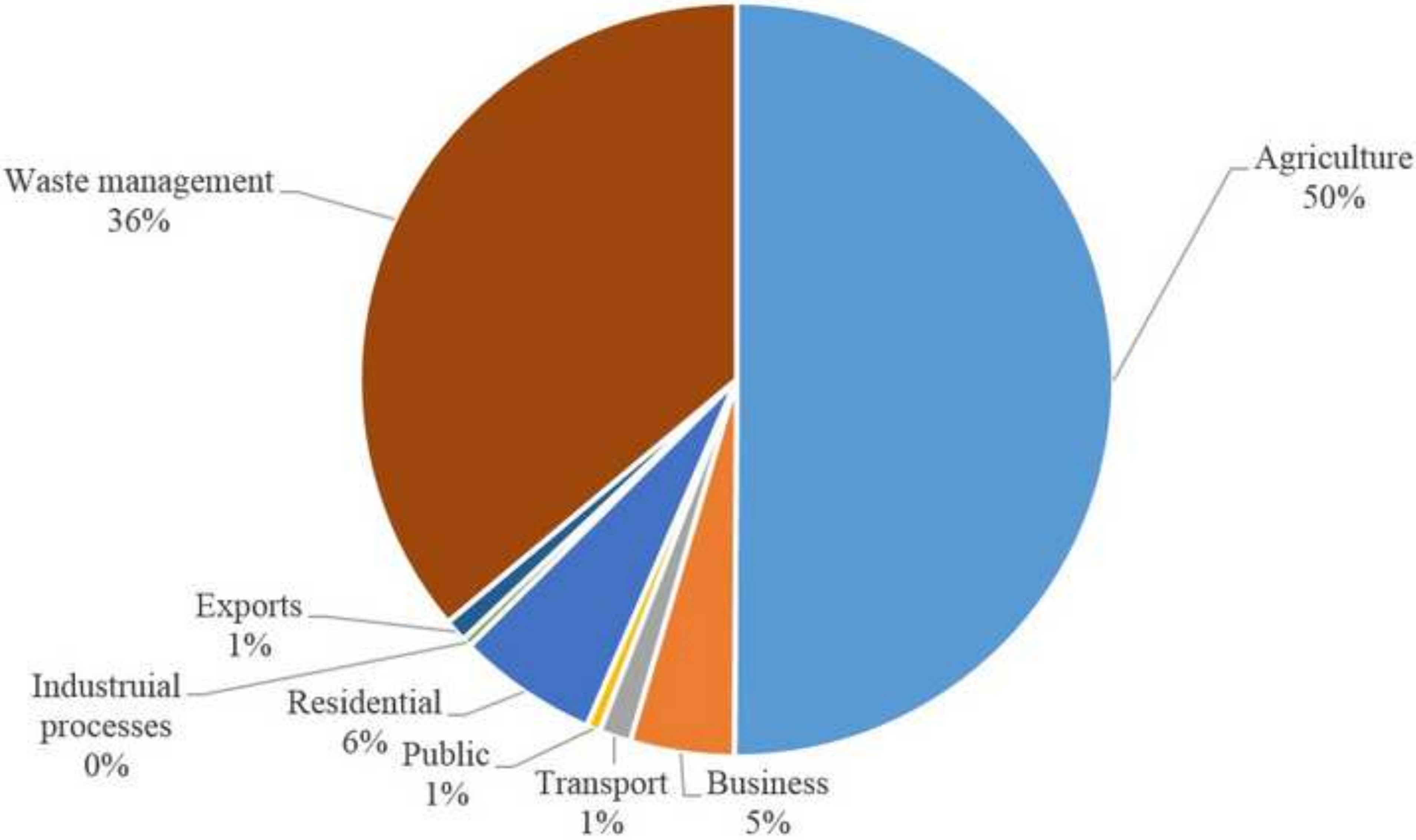

Waste management
36%
Agriculture
50%
Exports
1%
Industruial
processes
0%
Residential
6%
Public
1%
Transport
1%
Business
5%

Figure 6

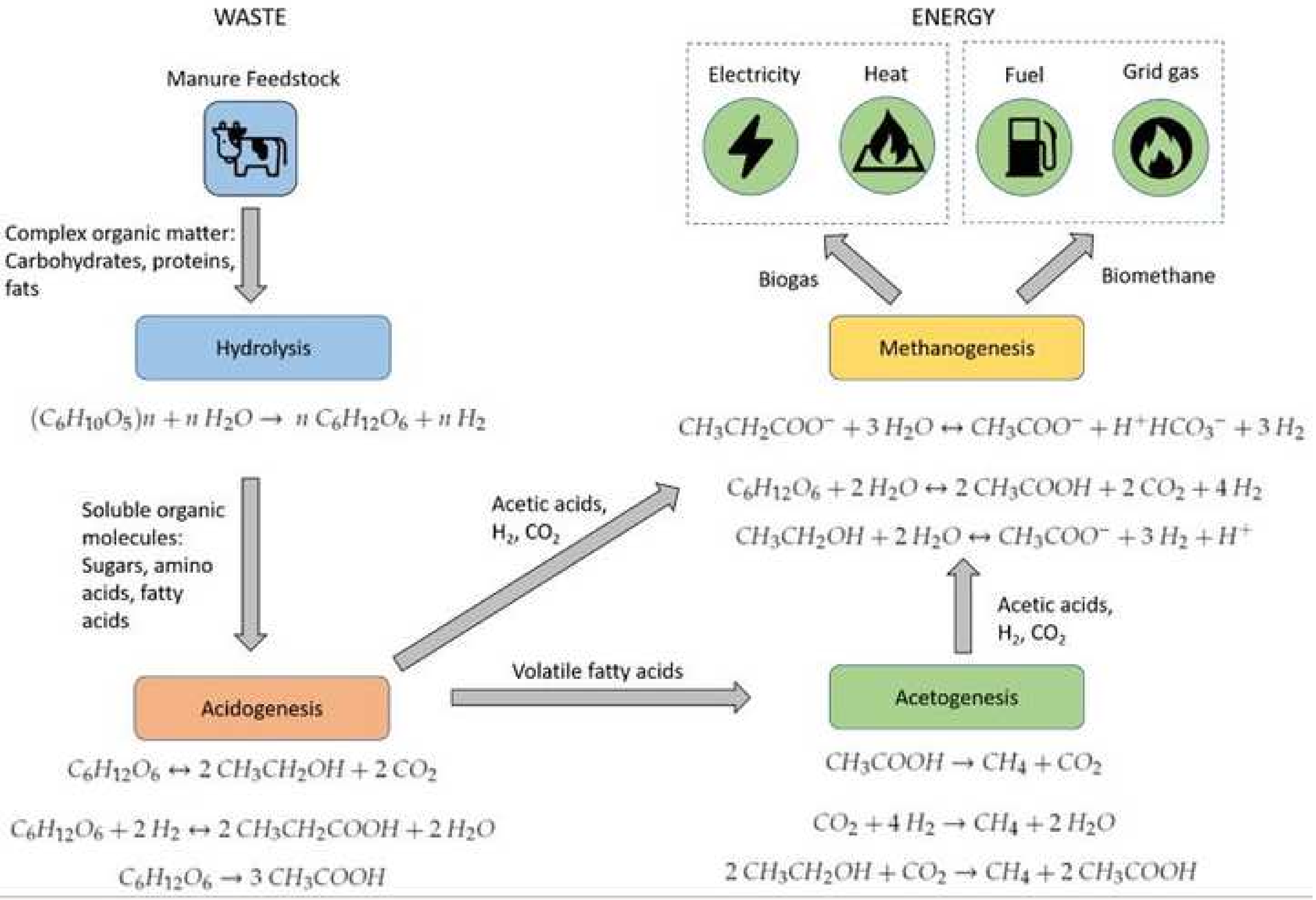
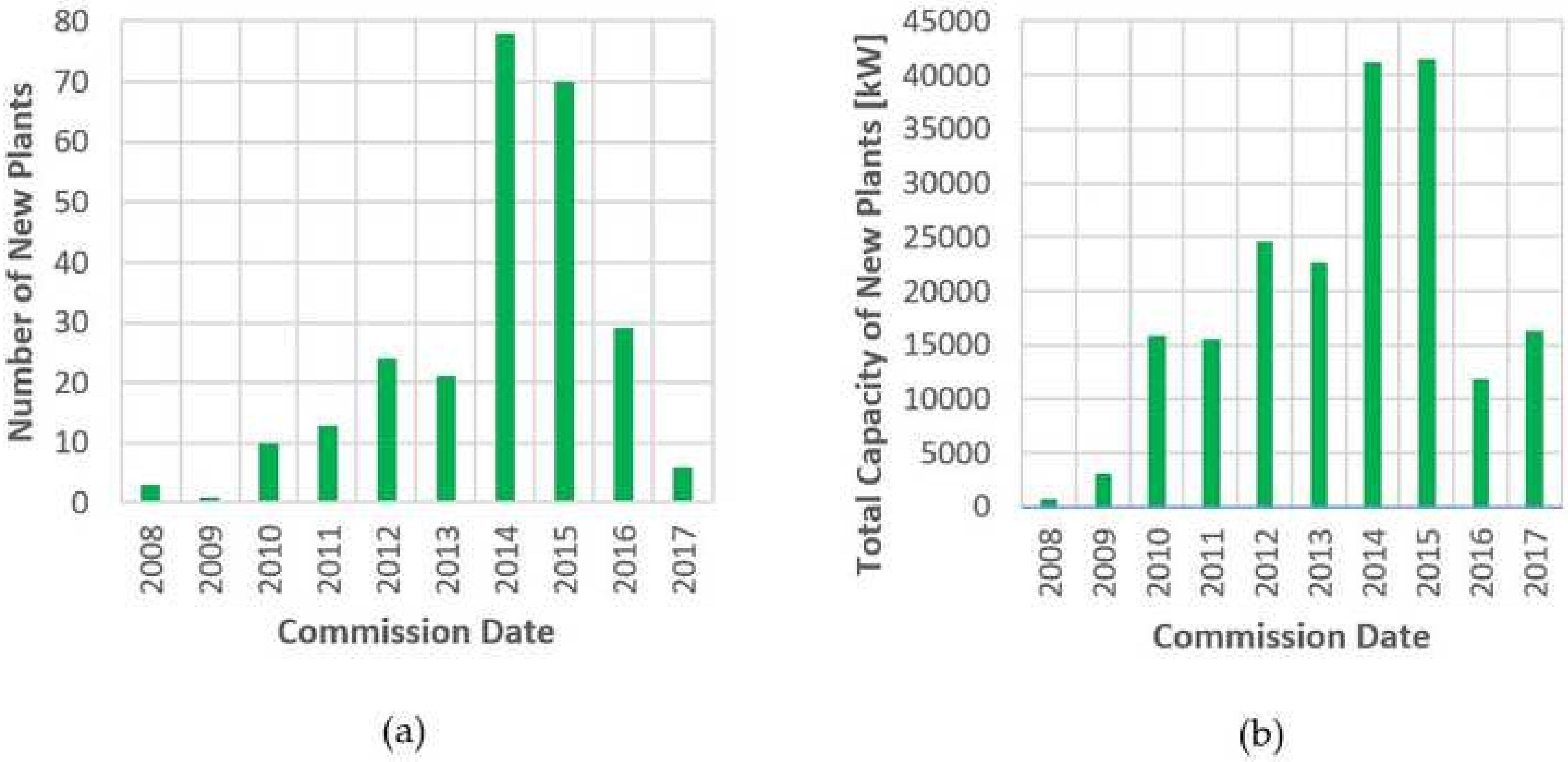

WASTE
Manure Feedstock
Complex organic matter: Carbohydrates, proteins, fats
Hydrolysis
$(C_6H_{10}O_5)n + n\,H_2O \rightarrow n\,C_6H_{12}O_6 + n\,H_2$
Soluble organic molecules: Sugars, amino acids, fatty acids
Acidogenesis
$C_6H_{12}O_6 \leftrightarrow 2\,CH_3CH_2OH + 2\,CO_2$
$C_6H_{12}O_6 + 2\,H_2 \leftrightarrow 2\,CH_3CH_2COOH + 2\,H_2O$
$C_6H_{12}O_6 \rightarrow 3\,CH_3COOH$
Acetic acids, H_2, CO_2
Volatile fatty acids
ENERGY
Electricity
Heat
Fuel
Grid gas
Biogas
Biomethane
Methanogenesis
$CH_3CH_2COO^- + 3\,H_2O \leftrightarrow CH_3COO^- + H^+HCO_3^- + 3\,H_2$
$C_6H_{12}O_6 + 2\,H_2O \leftrightarrow 2\,CH_3COOH + 2\,CO_2 + 4\,H_2$
$CH_3CH_2OH + 2\,H_2O \leftrightarrow CH_3COO^- + 3\,H_2 + H^+$
Acetic acids, H_2, CO_2
Acetogenesis
$CH_3COOH \rightarrow CH_4 + CO_2$
$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O$
$2\,CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2\,CH_3COOH$

Figure 7

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
0-250 kW	15.15	15.15	17.54	17.54	17.54	12.64	10.11	6.48	4.57	4.5
250-500 kW	15.15	15.15	16.23	16.23	16.23	11.69	9.34	5.98	4.33	4.27
500-5000 kW	11.82	11.82	10.69	10.69	10.69	10.16	9.63	6.16	1.61	1.54


Number of New Plants
80
70
60
50
40
30
20
10
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Commission Date
(a)
Total Capacity of New Plants [kW]
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Commission Date
(b)

Highlights:

- Lack of manure treatment in the UK results in 28% of all ammonia emissions
- NO_X emitted from agriculture accounts for 3% of the total NO_X emissions in the UK
- Manure and slurry contribute about 50% of anthropogenic UK’s methane emissions
- Drops in tariff rates result in fall in number of anaerobic digestion plants in UK
- AD of manure is uneconomical due to high capital cost and absence of gate fees
- AD could produce 1.615 TWh electricity, i.e. 0.45% of total UK’s annual demand

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

None