Identifying the Sustainable Niche for Anaerobic Digestion in a Low Carbon Future

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Executive Summary

Achieving climate stabilisation is an immense challenge that will require transformations in how we do things. Thus, the future context in which specific technologies operate will be different. Strategic planning is essential to target investment in technologies that don't just reduce emissions, but fit within the future circular, net zero greenhouse gas (GHG) economy that we need to build. There is an urgent need to evaluate the role of food waste management in this context, to support future-proofed solutions that avoid technological lock-in to expensive technologies that could become redundant. The objective of this report is to identify the role of anaerobic digestion (AD) in future GHG mitigation, energy and food security within the context of a low- or net zero-GHG, circular economy. We explore the extent to which other low-carbon energy sources and more circular solutions to food waste could constrain the "sustainable niche" for strategic AD deployment.

This analysis was based on an expanded boundary life cycle assessment of stylised (deliberately "extreme") scenarios, taking the same hypothetical baseline of zero burdens from counterfactual management of food waste. Extrapolation of current trajectories of AD deployment to a future "AD-max" scenario in the UK indicates that "excess" AD deployment could constrain waste prevention and higher value uses of waste for animal feed, whilst also appropriating arable land to cultivate crops for AD energy generation. Maximum deployment of AD was contrasted with a Circular scenario that minimises waste generation, maximises diversion of non-human-edible potential waste streams into animal feed (via heat treatment and insects, accompanied by regulatory change), uses all spared grassland for afforestation and all spared arable land for either food or solar PV electricity generation. The influence of wider decarbonisation on the comparative efficiency of AD was evaluated by considering three contexts along an ambitious decarbonisation gradient, in line with net zero GHG targets and the UK Committee of Climate Change scenarios: Current technology; 80% decarbonisation; net zero GHG emissions.

The Circular scenario achieved twice as much GHG mitigation as the AD-max scenario, ranging from 66.9 to 22.3 Mt CO_2 eq. under decarbonisation contexts ranging from Current Technology to Net Zero Carbon. Meanwhile, the AD-max scenario realised GHG mitigation ranging from 34.4 to 10.5 Mt CO_2 eq. as the wider economy decarbonised. The circular scenario could also support four times more energy generation, if land not required for energy crop cultivation is instead dedicated to electricity generation via solar PV, and three times more food protein production on land spared from animal feed production.

It was assumed that in future all behavioural and technical challenges to full separation of food waste from residual waste streams, along with safety and regulatory barriers to diversion of many food waste streams to animal feed, could be overcome. Whilst it is likely that the impetus towards net zero GHG emissions and a circular economy will steer waste management in this direction, these assumptions are not likely to be fully realised. Nonetheless, these assumptions enabled a clear comparison of two distinct policy pathways in terms of climate, food and energy security objectives. Results robustly support the following conclusions:

- AD will remain an efficient form of management for genuine organic wastes that supports net GHG mitigation even in a net zero carbon future when alternative energy and nutrient supplies have been heavily decarbonised.
- However, waste prevention and diversion of food waste to animal feed will remain far superior options to AD in terms of GHG mitigation and food security, even before land sparing is taken into account. In fact, food production is not expected to decarbonise to the same extent as energy generation, increasing the comparative advantage of prevention and animal feed diversion over AD.
- GHG mitigation via food waste prevention can be increased by up to five-fold if grassland spared from food production is afforested. This effect will remain dominant through time, though could be reduced by two thirds owing to projected intensification of livestock food systems.
- Use of land for AD-cropping is highly inefficient in terms of GHG mitigation and energy security. Using land for solar PV generation instead of AD could support up to 18 times more energy generation per hectare under typical UK conditions.
- Constraining AD to organic waste fractions that cannot be prevented or diverted to higher value uses, and efficiently utilising all spared land for forestry, renewable energy and food production, could increase GHG mitigation by two-fold, energy generation by four-fold and food protein supply by three-fold compared with more indiscriminate maximum deployment of AD in line with industry projections.

1. Introduction

Objective

The objective of this report is to identify the role of anaerobic digestion (AD) in future greenhouse gas (GHG) mitigation, energy and food security within the context of a low- or net zero- carbon, circular economy. We explore the extent to which other low-carbon energy sources and more circular solutions to food waste could constrain the "sustainable niche" for strategic AD deployment.

Circularity & climate stabilisation

Food waste poses a major global challenge in terms of social, economic and environmental sustainability. Governments, charitable organisations, corporations and individuals all have an important role to play to reduce and manage food waste in a more sustainable manner. The United Nations set Sustainable Development Goal 12.3 as a target to halve global food waste per capita by 2030[1] (Moult, Allan, Hewitt, & Berners-Lee, 2018a). WRAP (2018) propose targets to reduce food waste and associated greenhouse gas (GHG) emissions per person by 20% in the UK by 2025. These form part of a wider ambition to move all sectors towards the realization of a more circular economy (Borrello, Caracciolo, Lombardi, Pascucci, & Cembalo, 2017). Circularity requires *inter*-systems thinking to drive integration of sectors across the economy around extended value chains that produce, use, re-use and finally recycle resources. Meanwhile, the climate emergency is increasingly recognised by governments across the world who are establishing policy targets to achieve net zero GHG emissions by 2050 (e.g. CCC, 2019), in line with highly ambitious but essential commitments made under the Paris Agreement to limit climate change to well below 2°C, and preferably 1.5°C (Masson-Delmotte et al., 2019). Achieving climate stabilisation is an immense challenge that will require transformations in how we do things; incremental reductions in GHG intensities (aka carbon footprints) will be insufficient. Thus, the future context in which specific technologies operate will be different. Strategic planning is essential to target investment in technologies that don't just reduce emissions, but fit within the future circular, net zero GHG economy that we need to build. There is an urgent need to evaluate the role of food waste management in this context, to support future-proofed solutions that avoid technological lock-in to expensive technologies that could become redundant.

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[1] The explicit wording of SDG 12.3 is "By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses". Champions 12.3, the group of global leaders convened by the UN to champion SDG 12.3, recommend that "one should apply the "halve per capita" in practice to food losses, as well, not just to food waste" and that the target should cover "from the point that crops and livestock are ready for harvest or slaughter" through to consumer level. Citation:

Food waste

In the UK in 2015, about 10.2 million tonnes of food was wasted post-farmgate, equivalent to 156 kg per person (WRAP, 2020), with an extra 1.6 million tonnes estimated to occur at primary production within the UK, a total of 11.8 million tonnes (WRAP, 2019c). There is a growing international consensus that food waste disposal should follow the food waste hierarchy, in order of environmental benefit, enumerated as follows: (i) prevent food waste, (ii) redistribute it for human consumption (iii) recycle it as animal feed (iv) compost, anaerobic digestion and energy recovery, incineration (vi) landfill the remainder (Salemdeeb, zu Ermgassen, Kim, Balmford, & Al-Tabbaa, 2017b; WRAP, 2016). The amount of food that is reduced, redistributed and that which is converted to animal feed is likely to increase to meet food waste reduction obligations (WRAP, 2016). This could in turn have significant consequences, such as increase in the availability of land previously used for conventional food or feed production (zu Ermgassen, Phalan, Green, & Balmford, 2016b). Landfilling produces significant quantities of GHG emissions and is therefore being phased out under EU regulation (EC, 2014). For this reason, it is less likely to be a food waste disposal option in the future, even though it is was recently still the destination of up to 48% of food waste in parts of the UK (Salemdeeb et al., 2017b). Incineration and composting also produce greenhouse gases, and may contribute less to emission reduction in the future (Salemdeeb et al., 2017). One of the favoured options for treatment of food waste and other wet organic wastes in AD, which, when implemented efficiently, facilitates the recycling of nutrients whilst generating biomethane fuel as a co-product.

Anaerobic digestion

Anaerobic digestion is the process of organic matter decomposition by microbes in the absence of oxygen. Organic matter is converted into carbon dioxide (CO_2), methane (CH_4) and other trace gases such as hydrogen sulphide (H_2S), collectively termed “biogas”, plus a liquid digestate that contains residual organic matter and nutrients (nitrogen, phosphorus and potassium). Following capture of the biogas in sealed tanks or bags, the CH_4 content of the biogas can be combusted as a fuel, for example in a combined heat and power (CHP) plant. This provides a useful source of renewable bioelectricity, and heat, which can be used within the AD process in a number of different ways (e.g. for sterilisation of waste) or for external use (e.g. heating of nearby buildings). Alternatively, biogas can be purified into a clean CH_4 biofuel that can directly replace natural gas in heating or transport applications. Meanwhile, the digestate can be used as an effective biofertiliser, if handled appropriately. Thus, AD provides a potential integrated solution to waste management, energy generation and nutrient recycling compatible with low-carbon and circular economy principles. The deployment of AD facilities has accelerated over the past 20 years, due to the introduction of various incentive schemes by governments across Europe to cultivate its growth. For example, in the UK, payments through Feed-in Tariffs and Renewable Heat Incentives have improved its economic viability (Kampman et al., 2016). AD establishment could increase further with a growing introduction of source segregated food waste collections and the aforementioned need to reduce waste and emissions to achieve climate change targets (Walker et al., 2017). AD has thus been promoted across Europe as the most appropriate technology for the sustainable management of organic materials such as food waste and animal manures (Stiles et al., 2018). Concomitantly, there has been an increase in the growing of crops specifically as feedstock for AD, especially maize.

Germany was the earliest adopter of AD at scale in the EU and has the largest capacity (mainly using maize feedstocks), followed by Italy and the UK (Kampman et al., 2016). In September 2011, there were only 68 anaerobic digestion plants operational in the UK, rising to 140 in September 2014, which nearly quadrupled the installed capacity of electricity from AD (Department for Environment, Food and Rural Affairs, 2015, p. 3). During this period, the industry remained highly fragmented, with no operator owning more than five operational facilities in 2015 (Green Investment Bank, 2015, p. 6). By April 2019, there were 579 operational AD plants in the UK[i], including 88 biomethane-to-grid plants (where the biomethane is upgraded by 'scrubbing' of trace gases, to be fed directly into the gas grid), with a further 343 anaerobic digestion projects under development(NNFCC, 2020). Greater industry consolidation has occurred as the industry has matured, though there is still a large diversity of sizes and types of AD plants (DAC Beachcrott, 2019).

The industry plans significant growth. ADBA project that "with the right government support", the UK's AD industry has the potential to generate 80 TWh by 2030, enough to deliver around 30% of domestic electricity or gas demand, or to power nearly every HGV in the UK (Anaerobic Digestion & Biogas Association, 2018). The ADBA project that nearly half of electricity generated by AD by 2032 will come from farm animal wastes and bedding feedstocks, just over a quarter from crop feedstocks, and less than one fifth from inedible food waste feedstocks (Anaerobic Digestion & Biogas Association, 2018)[ii]. In light of these significant plans for expansion, it is important to critically evaluate the prospective sustainability of the AD industry within the context of potentially transformed energy and food systems.

Low carbon energy

There are many ways of delivering electricity, heat and transport with smaller environmental footprints than AD energy generation, and the current use of crops for biogas production in AD systems is arguably not sustainable (Styles et al., 2015; Styles et al., 2016). This is particularly the case because the net energy generated per hectare of land used for growing AD crops is small compared with other pathways for energy generation from that land, such as solid biomass crops (e.g. forestry or energy crops) and solar photovoltaic panels or wind turbines (Styles et al., 2016). The land required for AD crops is also typically high quality agricultural land, resulting in significant risk of food and feed crop displacement, leading to considerable GHG emissions consequences elsewhere via indirect land use change (iLUC). Nonetheless, it must be stated that the dispatchable nature of biomethane-derived energy does confer energy security benefits that may last well into the future, depending on progress with energy storage technologies. Thus, in a net zero GHG emission future (CCC, 2019), the range of situations in which AD is the most environmentally sustainable option to treat organic (waste) streams could be curtailed, despite its potential for organic waste treatment. There is an urgent need to apply consequential life cycle assessment (LCA) within a forward-looking study to identify the sustainable “niche” for AD under likely scenarios representing future energy and waste conversion technologies and land uses.

The objective of this study is to identify the most likely sustainable function of AD systems in the net zero carbon future in the UK, while accounting for the environmental impacts of the food waste sectors and alternative land uses resulting from food waste reductions. This is performed using a consequential LCA model.

Assessing environmental sustainability

Attributional LCA is a method of systems analysis that accounts for inputs, outputs and associated environmental impacts arising along the entire value chain of a product or service (Finkbeiner et al., 2006). It is well suited to benchmarking the environmental efficiency of systems at delivering particular goods and services, and identifying improvement options within those systems. However, when evaluating prospective technology deployment from a wider societal policy perspective, broader consequential LCA is more appropriate (Weidema et al., 2018). Consequential LCA is increasingly being applied to assess the sustainability of food, bioenergy and waste systems (Styles et al., 2018; Tonini et al., 2018; Tonini et al., 2012; Yesufu et al., 2019). Recent studies have also applied consequential life cycle assessment to demonstrate that AD deployment can lead to poor environmental outcomes where crops or wastes that can otherwise be used as animal feed are diverted into digesters (Styles et al., 2015; Styles et al., 2016). Nonetheless, these studies have also found that where there are no valuable alternative uses of organic wastes, such as for animal manures, AD can be the most environmentally sustainable option.

Moult et al., (2018) performed a LCA to calculate the net GHG emissions of eight different waste disposal options for five core food types in the retail sector, accounting for emissions incurred in transport, processing and disposal: donation for human consumption; conversion to wet animal feed; anaerobic digestion; composting; UK and global landfill, with methane capture. Salemdeeb et al., (2017) conducted a consequential LCA to investigate the potential benefits of diverting household and catering food waste for pig feed in the UK, comparing technologies for South Korean style-animal feed production with UK composting and AD disposal technologies. De Menna et al. (2019) performed an LCA to evaluate impacts of food waste from manufacturing, retail and catering sectors in the UK and France, assuming food waste is treated for animal feed as an alternative to incineration, landfill, composting and anaerobic digestion processing. Tonini et al.,(2018) was the only study to quantify the environmental impacts of avoidable food waste management under current UK technology across the four stages of the food supply chain: processing, wholesale and retail, food service, and households. These and other studies provide a clear picture of the environmental sustainability of AD in the context of current marginal technologies for waste management and energy generation. However, there remains a lack of evidence on the sustainability of future AD deployment, considering different marginal energy and waste management technologies and strong land competition between food production and carbon sequestration in the context of net zero carbon targets (IPCC, 2019).

Many studies have found that AD can have a positive environmental impact compared with alternatives like fossil fuel generated electricity and gas, or leaving waste products untreated (Barrera et al., 2016; Edwards et al., 2017; Evangelisti et al., 2014; Hijazi et al., 2016; Pacetti et al., 2015; Timonen et al., 2019). However, an increasing body of literature has begun to question the sustainability of AD, particularly when using certain feedstocks. For instance, LCAs have illustrated that growing maize for AD can have detrimental environmental outcomes, particularly as a result of its land use requirements (Adams & McManus, 2019; Herrmann, 2013; Purdy et al., 2017). LCAs have also found that sending animal wastes such as manure or slurries to AD has positive environmental effects, including mitigating GHG burdens (Lauer et al., 2018; Mesa-Dominguez et al., 2015; Styles et al., 2015) – although this mitigation is limited compared with the overall high environmental impact of meat production (Poore & Nemecek, 2018). A limited number of LCAs have been conducted comparing the different environmental outcomes of sending food waste to AD compared with other destinations. Salemdeeb et al., (2017a) concluded that sending food waste to produce animal feed (wet-feed) was better on 13 out of 14 environmental indicators than sending it to AD, including for global warming potential[iii]. Moult et al., (2018b) found that, in terms of GHG emissions, sending food waste to AD was favourable to sending it to landfill, incineration or composting, but was in almost all cases less beneficial than sending it to animal feed, and always considerably less beneficial than sending it to human consumption[iv]. These conclusions are broadly consistent with established food waste hierarchies that place AD as a less desirable destination, and categorise food sent to AD as food waste (not as "reduced") in reporting towards Sustainable Development Goal 12.3 (Hanson, 2017).

To achieve GHG emission reductions consistent with a "safe" constraint of 1.5°C of climate change, substantial emissions reductions from the agriculture and land use, land-use change and forestry (LULUCF) sectors will be required. Especially "fast and deep" cuts are required in rich countries if climate equity is to be achieved (Civil Society Review, 2018; Clim. Equity Ref. Calc., 2019; Jackson, 2019), potentially within a contraction and convergence model that gives poorer countries emissions headroom to develop. Recent studies have suggested that methods such as dietary change and food waste reduction will be essential to achieve reductions in GHG emissions related to the food system (Bajželj, 2014; Kim et al., 2015) – with meat particularly having disproportionately high emissions and land use (Clark et al. 2019; Poore & Nemecek, 2018). Afforestation and eco-system restoration have significant potential for carbon sequestration (Bastin et al., 2019). Therefore, land-sparing from reducing the production of land-intensive foods such as meat (particularly beef) presents very large carbon sequestration opportunities (Harwatt & Hayek, 2019). Innovative means of integrating surplus food back into the supply chain also need to be considered, such as tightly regulated feeding safely-treated surplus food containing meat as feed to omnivorous non-ruminants like pigs and chickens (Luyckx et al., 2019; zu Ermgassen et al., 2016a), and feeding food waste to insects for use as feed (Smetana et al., 2019; van Zanten et al., 2015).

In order to efficiently progress towards a circular, net zero GHG economy, there is an urgent need for more evidence on the sustainable niche for AD within likely future contexts – where it provides the best environmental outcome, and where it is suboptimal and competes with better alternatives for feedstocks and land use. Studies to date have mostly compared AD to high environmental impact alternatives (such as fossil fuel-derived electricity production) in present-day contexts, with which AD compares favourably (Bacenetti et al., 2013; Hijazi et al., 2016; Lijó et al., 2014; Rahman et al., 2019; Styles et al., 2016). However, to keep global temperature increase within a safe 1.5°C, rapid shifts in sustainability are necessary in short time frames. There is currently a gap in research comparing AD to ideal future marginal technologies and practises[v], such as afforestation of land, electricity production by wind and solar coupled with battery storage, dietary shifts to less meat consumption, and increasing the proportion of food going to human consumption and animal feed. Future contexts will likely involve important changes driven by technological development and coupled regulatory requirements: (i) reduced emissions intensities across AD systems (e.g. reduced CH_4 and NH_3 associated with improved digestate storage); (ii) reduced emission credits from substituted marginal energy generation; (iii) constrained availability of feedstocks linked with diet change, land scarcity and improved food waste management. This study aims to shed light on the sustainable niche for AD, in order to derive a set of recommendations for strategic deployment of AD within necessarily ambitious net zero carbon and circular economy targets.

2. Methodology

Goal and scope

The aim of this study is to ascertain the sustainable niche for AD in a low (and net zero) carbon, circular economy. Acknowledging uncertainties in future projections, a primary objective is to identify how the comparative environmental efficiency of AD is likely to change as it becomes optimised whilst the wider economy decarbonises. Particular emphasis is placed on (potential) food waste, which is categorised along five stages of the food supply chain associated with different prevention and management options: primary production (PP); manufacturing (M); Retail (R); Catering (C); Household (HH). Other dominant AD feedstocks are evaluated, namely, industrial wastes, manures and purpose-grown-crops. In terms of environmental impact, emphasis is placed on GHG mitigation, exploring implications for food and energy security via competition for land, addressing the food-energy-climate nexus.

This study builds on evidence compiled over the past decade on the environmental sustainability of AD. Framing decisions are based on the following assumptions:

- AD is the most GHG-efficient form of organic waste management, but less efficient that re-use of potential waste streams as animal feed or waste prevention (Styles et al., 2016; Tufvesson et al., 2013). For methodological clarity, we therefore consider three possible fates of potential food waste streams compatible with NZC and circular economy objectives: absolute prevention, animal feed, AD.
- Crop AD is not a land-efficient bioenergy option owing to low useful energy yields per hectare (Styles et al., 2015), and is not considered to be a sustainable deployment of AD within the circular economy scenario (described later).
- Land is a scarce resource with increasingly high opportunity cost (IPCC, 2019; UK CCC, 2020). Changes in land requirements associated with different AD and waste management strategies will have significant implications for GHG mitigation potential via e.g. afforestation, and/or for food security, and/or for energy security. Here, we quantify the magnitude of these implications using indicative scenarios within an expanded boundary LCA framework, building on a previous assessment of the environmental balance of UK-wide AD deployment based on current carbon- and land-intensities (Styles et al., 2016).
- The GHG- and land-intensities of energy, food, feed and fertiliser production will reduce through time at different rates, influencing the comparative efficiency of AD in terms of waste management, energy generation and nutrient recycling technology.

Displaced or additional food/feed production and other processes were accounted for as environmental credits or debits respectively within an expanded boundaries framework (Fig. 1). Avoided land occupation was translated into potential carbon sequestration via afforestation, to estimate maximum achievable GHG mitigation. Spared land could be used for a range of alternative uses. We also quantity the potential magnitude of energy and food security benefits achievable through land sparing via highly simplified indicative scenarios: total solar photovoltaic electricity generation on all spared land; staple food production, expressed as kcal plus kg protein production from a 50/50 area split of potatoes and peas. Inventories were calculated, and results presented, for a reference flow of one tonne (Mg) of fresh matter (FM) of food waste or alternative AD feedstock in the first instance, and for national scenarios representing maximum AD deployment or maximum circularity within current and future likely health & safety (legislative) constraints. The baseline is represented by the marginal prevailing management of AD feedstocks, including emissions and fertiliser credits associated with prevailing manure management. A significant proportion of food waste in the UK already goes to AD. A simplified baseline is therefore established for food waste in line with the objective to compare the GHG mitigation efficiency of maximum AD deployment against a scenario of maximum waste prevention: waste generation, with no avoided waste management burdens (i.e. all waste is either prevented, fed to animals or goes to AD). The implications of this assumption for the interpretation of calculated GHG mitigation values are fully discussed later.

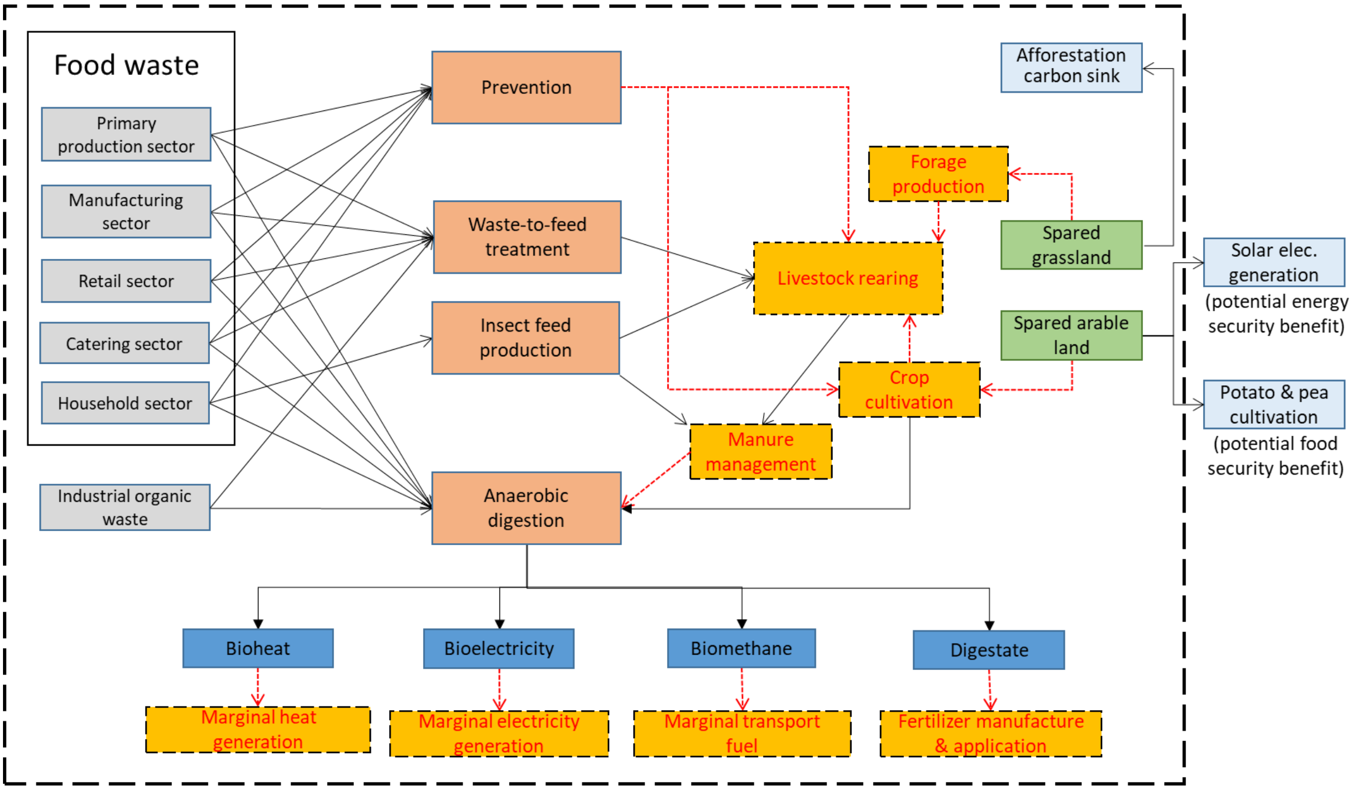

Figure 1. Major incurred and potentially avoided (dashed boxes) processes accounted for within the life cycle assessment boundary. Solar electricity generation and potato and pea cultivation not included within GWP calculations, but used to present alternative energy and food security implications of land sparing.

Two primary impact categories are considered within the LCA, to represent the climate emergency and the critical constraint of land availability: Global Warming Potential (GWP) measured as kg CO_2 eq. (CO_2, CH_4 and N_2O = 1, 25 and 298, respectively) and Land Occupation (LO) measured as m^2.year.

Life cycle inventories

Life cycle inventories, expressed as material flows and processes related to one Mg fresh matter AD feedstock, are displayed in SI A1-6, and details are elaborated in relation to the decarbonisation contexts and indicative deployment scenarios described below. Environmental burdens for all background processes were obtained from Ecoinvent v3.6 (Wernet et al., 2016), with modifications made to account for future reductions in GHG- and land- intensities of food and feed production, elaborated later. Energy outputs and fugitive emissions from AD are calculated in the LCAD tool described in Styles et al. (2016), with increasingly efficient parameterisation described below.

Waste & AD scenarios with decarbonisation contexts

In order to evaluate the influence of decarbonisation on the comparative GHG mitigation efficacy of AD, three indicative decarbonisation contexts were considered (Table 5). These represent: (1) current technology (i.e. current marginal energy generation and food and feed production); (2) major (80%) decarbonisation, in line with UK Committee on Climate Change "Core" projections (CCC, 2019), and; (3) realisation of Net Zero Carbon through ambitious decarbonisation plus offset (CCC, 2019). For example, electricity generated from biogas replaces electricity generation from natural gas without or with carbon capture & storage (CCS), or from solar photovoltaic, across the increasingly ambitious decarbonisation contexts (Table 5). The carbon footprint of marginal electricity generation declines by 78% from "Current Technology" (context 1) through to "Net Zero Carbon" (context 3). Emissions intensities and land requirements for food and feed production also decline across the increasingly ambitious decarbonisation scenarios, but less markedly than for energy generation – based on sustainable intensification projections for major UK crop and animal systems in a recent land sparing study (Lamb et al., 2016). For most food and feed products, carbon footprints decline by around 50%, and land requirements by 25-65%. Current values are taken from Ecoinvent v3.6 (Wernet et al., 2016).

Three main food waste management options were explored for each stage in the food supply chain: (i) waste prevention; (ii) diversion to animal feed (following heat treatment for retail and catering wastes); (iii) anaerobic digestion. The performance of all three options was first compared for one Mg FM. Then, quantities and associated environmental burdens and credits were scaled out to two indicative national (UK) scenarios representing different waste management priorities:

- An AD-max scenario, in which industry trends documented by WRAP (WRAP, 2019c, 2020) were extrapolated to 2030[2] and combined with AD industry estimates of AD deployment

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[2] WRAP also project 50% reduction in food waste by 2030, but they use baselines for different sectors from 2007 onwards, only project a 50% reduction in edible food waste, and do not currently include a concrete target for reducing primary production food waste due to lack of data. Hence, they project a reduction from 10.2 mt of post-farmgate food waste to 7.7mt by 2030, with no specific targets for primary production. In contrast, the Circular economy scenario aims for 50% reduction in farm to fork food waste using a 2015 baseline (as a percentage of edible and inedible food waste), which equates to a reduction from 11.8 mt to 5.9 mt. The Circular economy scenario also assumes some food surplus is moved up the hierarchy from animal feed to prevention.

(ADBA report) for food waste, industrial wastes, manures and crops to estimate the upper end of future AD deployment based on current policy;

- A Circular economy scenario, where AD was used only for waste streams that couldn't be diverted to higher value uses first, such as human consumption (prevention) or animal feed. This scenario was based on meeting the SDG target for a 50% reduction in total food waste (using a 2015 baseline, with 50% reduction out of total edible and inedible food waste) and regulatory change to allow catering waste and some meat products to go into the non-ruminant animal feed chain following suitable heat treatment.

These two scenarios are independent of the three decarbonisation contexts, with the following exceptions for the Net Zero Carbon context. In this context of radical decarbonisation, it is assumed that the regulatory barriers to using household food waste for animal feed can be circumvented through diversion of 50% of this waste stream into insect feed production (van Zanten et al., 2015) – elaborated later. The manure produced by the insects is then fed into AD, alongside a reduced quantity of animal manure, representing a dietary shift away from meat consumption in the Net Zero Carbon decarbonisation pathway (CCC, 2019) – elaborated later.

Table 1 summarises key parameters across the three decarbonisation contexts for the two scenarios. It is worth noting that AD process parameters (fugitive emission leakage rates, biogas yields and digestate management) are set at "average" for the current technology context, but optimised for the 80% decarbonisation and NZC scenarios, based on performance ranges identified in Styles et al. (2016). Use of biogas is adapted to fit the anticipated best "niche" in each prevailing context. In the current technology context, maximum mitigation can be derived from substitution of diesel via upgrade of biogas to biomethane transport fuel. In the 80% decarbonisation pathway, natural gas remains an important fuel for electricity generation and CCS technology is widely deployed (CCC, 2019). Therefore, combustion of biogas in CHP generators with CCS can replace fossil fuel generation and realise bioenergy carbon capture & storage (BECCS) – a net carbon sink unique to bioenergy. For this reason, biogas electricity generation with BECCS is also considered the most appropriate use of biogas in the ambitious NZC scenario, where heat, electricity and transport have largely (90% plus) decarbonised. Similarly, manure management (storage and application) emissions avoided through diversion of manures to AD also reduce with increasing decarbonisation, though to a lesser extent (50%) compared with energy generation as these emissions of CH_4 and N_2O are more difficult to cost-effectively abate.

For each of the scenarios and contexts, an expanded boundary LCA was applied as per Fig. 1, to calculate the total GHG emissions savings achievable from maximisation of either AD deployment or circularity. Potential GHG mitigation via afforestation was calculated for all grassland areas spared from food production via waste prevention. Potential energy and protein production for human consumption was estimated from cultivation of potatoes and peas on land spared from animal feed production. Meanwhile, potential energy generation was calculated for solar PV generation on arable land spared from AD-cropping in the circular scenarios. Thus, the performance of AD-Max and Circular scenarios was compared across climate mitigation, food security and energy security objectives.

Table 1. Evolution of key parameters pertinent to calculating the GHG and land balance of food waste from primary production (PP), manufacturing (M), retailing (R), catering (C) and households (HH) according to three decarbonisation (prevailing technology) contexts. Red text related to avoided processes.

		Context		
		Current technology	**80% GHG reduction pathway**	**Net zero GHG**
Food waste flows	AD$_{max}$ scenario	All projected separated food waste* goes to AD. See S1	All projected separated food waste goes to AD	All projected separated food waste goes to AD
	Circular scenario (with regulatory change)	Prevention and diversion to animal feed of fractions of projected PP, M & R waste streams. Prevention of fractions of projected HH waste. See S1	Prevention and diversion to animal feed of fractions of projected PP, M & R waste streams. Prevention of fractions of projected HH waste. See S1	Prevention and diversion to animal feed of fractions of projected PP, M & R waste streams. Prevention of fractions of projected HH waste, and 50% of remaining HH waste to animal feed via insects. See S1
Manure flows	AD$_{max}$ scenario	87% handled cattle, pig & layer slurry diverted to AD	87% handled cattle, pig & layer slurry diverted to AD	100% cattle, pig, layer & insect slurry diverted to AD, but 50% reduction in livestock
	Circular scenario	87% handled cattle, pig & layer slurry diverted to AD	87% handled cattle, pig & layer slurry diverted to AD	100% cattle, pig & layer slurry diverted to AD, but 50% reduction in livestock
	Counterfactual management of manures	Open tank storage, splash-plate spreading	50% reduction in counterfactual manure storage & spreading emissions	50% reduction in counterfactual manure storage & spreading emissions
Energy generation & substitution	Anaerobic digestion process efficiency	Medium (average gas leakage & energy conversion efficiency)	Optimised (low gas leakage & high energy conversion efficiency)	Optimised (low gas leakage & high energy conversion efficiency)
	Biomethane use (% biomethane energy)	Grid injection (45%) & transport (45%), digester operation (10%)	Grid injection (50%), CHP electricity generation (50%), with heat used for digester	Grid injection (50%), CHP electricity generation (50%), with heat used for digester
	Marginal (substituted) electricity	N/A in this context	Nat gas Carbon capture & storage	Solar PV or wind
	Carbon capture & storage	N/A in this context	Applied to all gas combusted for electricity generation	Applied to all gas combusted for electricity generation
	Marginal (substituted) heat	Nat gas	Nat gas	Heat pump, COP 4 driven by solar PV or wind electricity

	Marginal (substituted) transport fuel	Diesel	N/A in this context, because all transport is electric	N/A in this context, because all transport is electric
Avoided food & feed production	Marginal (substituted) animal feed	Soybean meal (protein) & maize (energy)	Soybean meal (protein) & maize (energy)	Soybean meal (protein) & maize (energy)
	Marginal food & feed production	Current burdens (Ecoinvent v3.6)	Intermediate current and Net Zero GHG emission burdens	Ecoinvent v3.6 land & GHG intensities scaled down according to Lamb et al. (2016) projected 2050 burdens
Digestate use & fertiliser substitution	Fertiliser manufacture	Current burdens (Ecoinvent v3.6)	50% of current burdens	10% of current burdens
	Fertiliser application (N_2O)	IPCC (2006) emission factors		
Projected waste stream quantities based on WRAP (2016, 2019, 2020). *"waste" excludes "surplus", defined as streams redistributed for human consumption, sent to animal feed, or used for bio-products.				

Food waste categories

Waste was categorised according to its origin along five stages of the food supply chain (Table 2) based on WRAP (2016). This study thus expands on a previous study which focussed only on manufacturing, retail and catering sectors due to limited data (De Menna et al., 2019) – by including primary production and household food wastes. Table 2 displays the quantities of food waste managed according to the possible options under the AD-max and Circular scenarios. A more detailed breakdown of waste categories is provided in the supplementary information MS Excel file – see SI B1.

Table 2. Annual quantities of food waste across the five stages of the food supply chain prevented or diverted to animal feed or anaerobic digestion

	Scenario	Prevention[a]	Animal feed direct	Animal feed via insects	Anaerobic digestion[c]	TOTAL
		Mg yr^{-1} FM				
Primary production	AD-max	260,300	1,994,000		1,345,700	**3,600,000**
	Circular	1,286,000	1,511,000		803,000	**3,600,000**
Manufacturing	AD-max	375,686	865,933		1,285,387	**2,527,005**
	Circular	901,000	731,000		893,688	**2,525,688**
Retail	AD-max	112,870	45,330		134,195	**292,395**
	Circular	117,500	45,000		130,500	**293,000**
Catering	AD-max	141,000			878,995	**1,019,995**
	Circular	357,000	153,000		510,000	**1,020,000**
Household	AD-max	1,491,110			5,608,570	**7,099,680**
	Circular	3,551,000		(1,776,860)[b]	3,553,719 (1,776,860)[b]	**7,104,719**
Food waste AD-max		**2,380,966**	**2,905,263**		**9,252,847**	**14,539,076**
Food waste Circular		**6,212,500**	**2,440,000**	**(1,776,860)**	**5,890,907 (4,114,048)**[b]	**14,543,407**

[a] Includes direct prevention through reduced production or human consumption, and possible prevention via distribution to charities; [b]only in the Net Zero Carbon ambitious decarbonisation context; [c]Assumes max diversion of all food wastes to AD, away from composting, land spreading and incineration.

Food that was diverted for human consumption or for which net demand was reduced through better management was classified as prevented food waste. This occurred in all sectors (Table 2), leading to avoided production of different types of products, and associated environmental credits – directly and indirectly via spared land (described later). The largest volume of food waste sent to AD in both AD-max and Circular scenarios is from households, reflecting both the dominance of post-consumer waste generation in the UK and also the difficulty diverting this waste to alternative, higher-value uses such as animal feed owing to food safety regulations. The HH stage is followed by PP, M, C and R in terms of volumes sent to AD (Table 2). Food waste from each source has distinct composition, influencing upstream footprints and downstream nutrient cycling, feed replacement and emissions. Therefore, each food waste category was analysed separately for AD-Max and Circular scenarios, and for the three decarbonisation contexts, resulting in 30 food waste streams. Results were then aggregated for summation with other major feedstocks going to AD in the AD-max and Circular scenarios (Table 3), largely based on industry estimates of maximum biomethane generation in the UK by 2030 (ADBA, 2019). Total food waste going to AD based on aggregation of quantities in Table 2 was 9,252,847 Mg yr^{-1} in the AD-Max scenario, somewhat higher than 7,240,688 Mg yr^{-1} back-calculated from the industry projected maximum biomethane production from food waste of circa 8 TWh (ADBA, 2019). This reflects our assumption that all food waste going to composting, landfill or incineration could be diverted to AD in the future (with the remainder split across prevention or animal feed). Compared with the AD-max scenario, the Circular scenario was based on maximum realistic diversion of wastes to higher value uses, including absolute prevention through reduced production or human consumption, diversion to animal feed, along with avoidance of the use of purpose-grown crops for AD. Total food waste going to AD was reduced by 36% in the Current Tech and 80% decarbonisation scenarios, and by 56% in the NZC scenario (owing to diversion of 50% of food waste to animal feed via insects).

Non-food-waste AD feedstocks

Table 3 displays the annual quantities of manures collected from housed animals in England and Wales based on a 2009 inventory (ADAS, 2009), whilst Table 4 summarises the total quantities of all feedstocks going to AD or alternative management options in the different scenarios and decarbonisation contexts. Note, additional bedding materials mixed with some forms of manure have been excluded owing to lack of data.

Table 3. Annual quantities of handled manures in England & Wales

Type	Quantity	
	Mg FM	Mg DM
Cattle	59,800,000	9,820,000
Sheep	1,500,000	375,000
Pigs	6,500,000	911,000
Poultry	3,600,000	1,440,000
Total	**71,400,000**	**12,546,000**

Industry projections for the upper end of biogas production by 2030 (ADBA, 2019) suggest that approximately 20 TWh of biomethane could be produced from farm animal wastes and bedding. Based on the manure proportions detailed in Table 3, and the top end of specific biomethane yields in the *LCAD EcoScreen* tool (Styles et al., 2016), this would equate to 10,942,518 Mg DM – which is 87% of the manure quantity collected in 2008 (Table 3). For Current Tech. and 80% decarbonisation contexts, it was assumed that 10,942,518 Mg DM was digested, but for the NZC context, it was assumed that handled manures declined by 50% to 6,273,000, representing a dietary shift away from meat (CCC, 2019) and possibly a shift towards less intensive livestock management to deliver other ecosystem service objectives (Garnett et al., 2017). Thus, the volume of manure sent to AD is reduced by 43% in the NZC context. Biomethane production potential presented by ADBA (2019) includes a significant share from "industrial wastes", such as solid residues from alcohol production, etc. In the absence of a detailed breakdown of what is included in this waste category, we used aggregate food waste as a proxy. Based on projected biomethane production, the total volume of organic industrial waste was estimated at 905,806 Mg FM (Table 4).

Table 4. Quantities of feedstocks going to different end-of-life options under AD-max and Circular scenarios, across the three decarbonisation contexts, expressed as Mg fresh matter (FM) per year for the UK.

		Current technology		**80% decarbonisation**		**Net zero carbon**	
		AD-max	**Circular**	**AD-max**	**Circular**	**AD-max**	**Circular**
		Mg yr^{-1} FM					
Food waste	Prevention	2,380,966	6,212,500	2,380,966	6,212,500	2,380,966	6,212,500
	Animal feed	2,905,263	2,440,000	2,905,263	2,440,000	2,905,263	2,440,000
	Animal feed-insects	0	0	0	0	0	1,776,860
	AD	9,252,847	5,890,907	9,252,847	5,890,907	9,252,847	4,114,048
Industrial waste	Animal feed	0	452,543	0	452,543	0	452,543
	AD	905,086	452,543	905,086	452,543	905,086	452,543
Maize	AD	6,101,636	0	6,101,636	0	6,101,636	0
Grass	AD	7,321,964	0	7,321,964	0	7,321,964	0
Pig slurry	AD	19,149,406	19,149,406	19,149,406	19,149,406	10,977,750	10,977,750
Cattle slurry	AD	87,540,143	87,540,143	87,540,143	87,540,143	50,184,000	50,184,000
Poultry manure	AD	13,131,021	13,131,021	13,131,021	13,131,021	7,527,600	7527600
Insect manure	AD	0	0			0	1,143,926

Composition of food waste

Food waste composition data were used to characterise food waste streams originating from each of the five stages of the food chain and destined for the three uses influenced by composition (prevention, animal feed and AD). These compositions depended upon, *inter alia*, the types of waste that could be avoided and sent to animal feed, and preferred pathways which differed by scenario (and to a lesser extent by decarbonisation context). Thus, over 30 food waste streams were characterised. Baseline food waste and surplus composition data were taken from WRAP data for 2015 (WRAP, 2016, 2018a; "WRAP restates UK food waste figures to support united global action," 2018), except for primary production food waste, for which only estimates are available from 2019 (WRAP, 2019b). Further detail on the partitioning of food waste streams is provided in the Appendix.

For modelling purposes, where food categories were aggregated (e.g. "Meat" or "Meat & fish" or "Dairy & eggs" or "fruit & vegetables"), some assumptions had to be made regarding relevant specific product representation and breakouts based on data for UK animal product consumption in 2013 and proxies, detailed in Table 5. Key characteristics, and the quantities of animal feed avoided, are expressed per Mg FM of each waste stream in SI A.

Table 5. Assumed composition of aggregated or undefined reported food components, for nutritional calculations and foot-printing purposes (based on available data)

Component	**Nutrition proxies**	**Footprint proxies**
Ambient	Weighted average of other components in the same stage of the chain	
Bakery		Bread
Confectionery		50% sugar, 25% milk solids, 25% cocoa
Dairy	36.4% cheese, 0.5% fresh milk, 63.1% eggs	Cheese
Drinks		Fresh oranges
Frozen	Weighted average of other components in the same stage of the chain	
Home/ready meals	Weighted average of other components in the same stage of the chain	
Meat, fish & poultry	21% beef, 6% lamb, 30% pork, 35% poultry, 9% fish	
Pasta and rice	50% pasta, 50% rice	
Produce	18 vegetables (52%) plus 16 fruits (48%).	50% apples, 50% carrots

Insect feed production

For HH food waste in the NZC context, production of animal feed via insects was modelled based on an LCA of producing house fly (*Hermetia illucens*) meal from a mixture of mainly food waste with some chicken manure (van Zanten et al., 2015). We simplified the LCA by considering that all dry matter feed was provided by HH food waste. Based on their study, producing one Mg of DM larvae meal requires 12.2 Mg food waste, 378 kWh of electricity and 183 kWh of natural gas for heating.

Energy is sourced from renewables in the NZC context (see Table 1 and SI 2), with GHG intensities reduced by 78% and 84%, respectively, compared with current technology. Meanwhile, almost half of the GHG emissions (379 out of 770 kg CO_2e Mg DM) originated from “egg production” and “larvae production”, much of this being accounted for by emissions from handling of the chicken manure used to feed the larvae, which don’t apply in our scenario. We therefore only considered heat, electricity and transport (1224 tkm per Mg DM meal) requirements for calculating processing emissions. Based on data presented by van Zanten et al. (2015), approximately 7.88 Mg of insect manure is produced per Mg larvae meal, with an N content of 12.46, 6.53 and 4.49 kg N, P_2O_5 and K_2O, respectively, per Mg. One Mg of DM larvae meal can replace 0.5 Mg DM soybean meal.

Calculation of avoided feed production

It was assumed that Manufacturing, Retail and Catering food waste categories diverted to animal feed were first heat treated, based on heating and electricity requirements summarised in De Menna et al. (2019). Marginal heat and electricity sources were considered (Table 1). The aggregate energy and protein contents of each tonne of each category of food waste were used to calculate the amounts of marginal feed ingredients avoided using linear optimisation to balance out digestible energy and crude protein, based on nutritional characteristics of maize grain as a marginal energy feed and soybean meal as a marginal protein feed (Table 7). The avoided burdens and amount of land sparing associated with animal feed substitution were then calculated based on Ecoinvent v3.6 burdens (Wernet et al., 2016) for the ingredients listed in Table 7, reduced by multipliers described below under decarbonised future scenarios.

Table 7. Nutritional characteristics of marginal feed ingredients substituted by food waste derived animal feeds

	Dry matter (%)	**Digestible energy (MJ kg^{-1})**	**Crude protein (kg kg^{-1})**	**Lysine (g kg^{-1})**
Soybean	88	15.22	0.49	26.7
Maize grain	86	14.24	0.08	2.5

Environmental footprint of (avoided) food & feed production

The environmental footprints of current (business as usual) food and feed production were taken from Ecoinvent v3.6 (Wernet et al., 2016) - see SI 2. Land footprints of food and feed production in the zero net GHG (ambitious decarbonisation) scenario were adapted based on Lamb et al. (2016).

Land occupation areas were updated based on technical potential yields for cereals, oil seeds, potatoes, sugar beet, fruit & vegetables and grass summarised in Table 1 of Lamb et al. (2016). For beef, dairy and lamb production, land area requirement was further reduced through multiplication by the ratio of feed conversion factor improvement (MJ feed required per kg meat or milk in 2050 divided by MJ feed required per kg meat or milk in 2010). GWP and FRDP footprints for crop-derived products were scaled down by a further 50% to reflect advancements in decarbonisation of energy, largely through a large scale switch towards renewable sources (SI 2), which will reduce the embodied global warming potential (GWP) and fossil resource depletion potential (FRDP) burdens of fertiliser manufacture, field operations, processing and transport. Following land efficiency scaling, animal pork and poultry GHG burdens were scaled down by a further 25% to represent reductions in feed production emissions intensities and potential advancements in housing and manure management technologies that could reduce animal-related emissions. Beef, dairy and sheep production GHG emissions were not scaled down beyond feed conversion ratio and grassland use efficiency ratios to reflect constraints to mitigation of enteric methane emissions that dominate carbon footprints from cattle and sheep systems (FAO, 2018). Food and feed footprints in the intermediate (CCC projection) scenario were fixed as intermediate between BAU and ambitious decarbonisation.

Zero animal feed or biogas yields were attributed to drinks, but avoided production burdens for drinks assumed equal to fresh orange production on a fresh weight basis as a simple proxy. For (avoided) burden estimations, “frozen food” was represented by the proxies 50% carrot & 50% chicken (by weight), “produce” was represented as 50% apples & 50% carrots, “ready meals” and “home prepared meals” were represented as 9% beef, 24% chicken, 34% potato, 33% carrot, and confectionary was approximated to milk chocolate with a composition of 50% sugar, 25% cocoa bean, 25% milk solids (equating to approximately 2.5 L milk per 1 kg chocolate).

Spared land utilization arising from waste prevention and more animal feed from waste

Spared land areas from waste prevention of substitution of animal feeds were calculated based on land footprints of avoided food and feed ingredients from Ecoinvent v3.6 (Wernet et al., 2016), adjusted for future yield increases (Lamb et al., 2016) as described above. Total land occupation areas reported in Ecoinvent for specific products were subsequently split into estimates of cropland and grassland areas on the following basis: all crops, 100% arable; fruit & veg. 50% arable; dairy derived products, 20% arable; meat derived products 5% arable.

Land which has been spared due to reduction in food or feed demand could be diverted to other priority uses in line with GHG mitigation and circular economy objectives. For indicative purposes, we elaborate scenarios with the following indicative uses of spared land: arable land spared from food and feed production is equally split into carbohydrate (potatoes) and plant-protein (pea) production, contributing to food security; arable land spared from AD-cropping in the Circular scenarios relative to the AD-Max scenarios is dedicated to solar PV electricity generation, contributing to energy security; grassland spared from food production is afforested, contributing to GHG mitigation and potentially longer-term energy security and bioeconomy objectives depending on use of harvested wood. Potatoes and peas are harvested at average UK yields (2013-2017) of 41.64 Mg ha^{-1} yr^{-1} and 4.4 Mg ha^{-1} yr^{-1}, respectively (UN FAO Stat, 2019) for the “Current Technology” scenario; these yields increase in line with aforementioned crop productivity improvements based on Lamb et al. (2016). Solar PV electricity generation is calculated based on annual electricity output of 44 kWh m^{-2} yr^{-1} in typical UK conditions, conservatively held constant through time (http://westmillsolar.coop/the-solar-park/). An average rate of C sequestration in soil and biomass following afforestation of 3600 kg C ha^{-1} yr^{-1} was assumed, based on average values for temperate forest regeneration provided in (Searchinger et al., 2018).

3. Results & discussion

Environmental balance of AD through time

Figure 2 displays the GHG balance of AD across six of the main feedstock types, and across the three decarbonisation contexts. Results are expressed per Mg FM, hence lower mitigation for the slurries owing to their high water content (90-96%). The largest GHG mitigation is achieved under the Current Tech context, owing to high GHG intensities of substituted energy (transport diesel), fertilisers and conventional manure management. Mitigation reduces modestly under the 80% decarbonisation context – a 40% reduction in GHG mitigation via fossil energy avoidance was largely ameliorated by carbon offset achieved via BECCS. There is a bigger proportionate reduction in slurry AD mitigation owing to the shift towards closed storage tanks. However, there is a large reduction in mitigation achieved by AD as more radical decarbonisation progresses. Avoided energy generation realises very little mitigation owing to effective decarbonisation of energy supplies, and in the case of grass AD, BECCS is not sufficient to offset process and digestate management emissions, which include grass cultivation along with fugitive emissions from the digester.

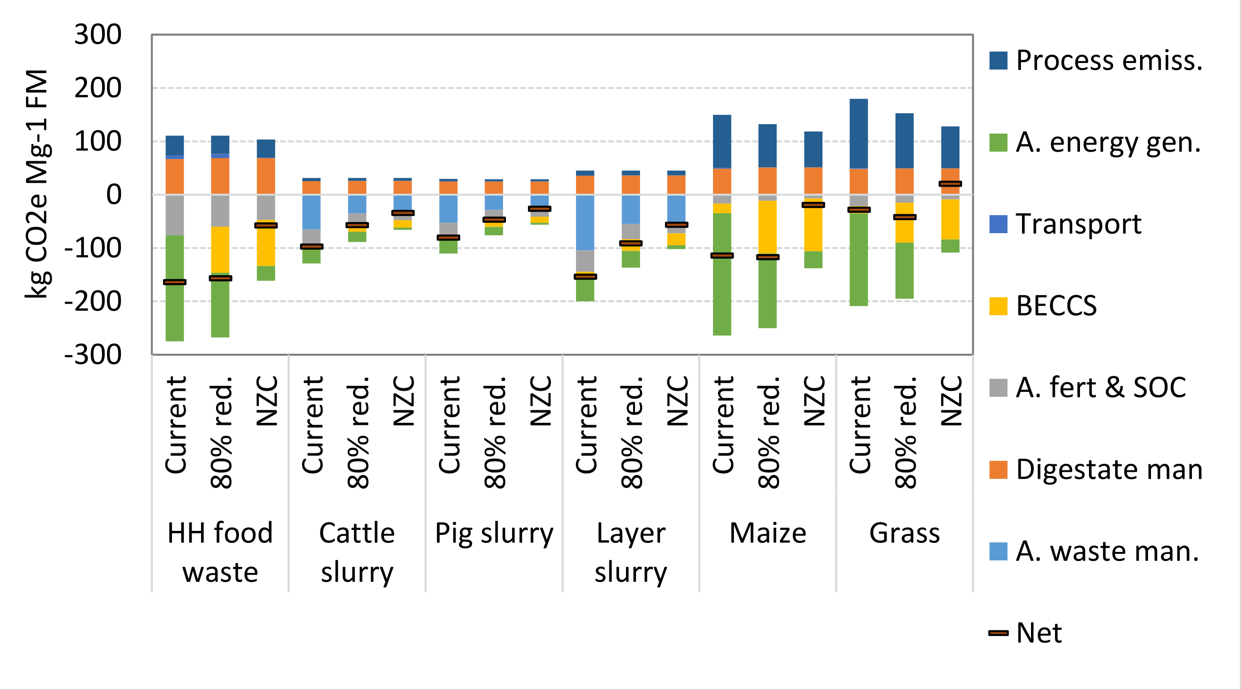

Figure 2. Greenhouse gas balance of anaerobic digestion of different feedstocks through time, from current technology, through 80% decarbonisation to net zero carbon (NZC). Net balance represents sum of emissions from incurred processes (e.g. transport of feedstock, fugitive and combustion emissions from AD process, emissions from digestate management) minus: (i) avoided (A.) emissions from e.g. manure management and synthetic fertilisers; (ii) soil organic carbon storage (SOC) associated with digestate application; (iii) bioenergy carbon capture & storage (BECCS).

Performance per tonne of potential AD feedstock

Under current technology, prevention is by far the most effective GHG mitigation option for food waste, supporting mitigation of up to 1,747 kg CO_2 eq. Mg^{-1} food waste owing to avoided food production (Figure 2). Afforestation of spared grassland could be afforested to sequester CO_2 from the atmosphere, increasing potential mitigation by 5,796 kg CO_2 eq. Mg^{-1} food waste. In comparison, AD of food waste supports net mitigation of 190 kg CO_2 eq. Mg^{-1}, whilst using relevant fractions of that food waste as animal (pig) feed supports 524 kg CO_2 eq. Mg^{-1}. If spared arable land was afforested, and additional 896 kg CO_2 eq. Mg^{-1} could be mitigated via animal feed, though this effect is not included in final scenarios which instead assume food is grown on land spared from producing animal feed. Most captured manures are sent to AD in the current technology context, achieving comparatively modest mitigation per Mg owing to the high water content (and thus low energy density) of manures, though mitigation is actually dominated by avoided manure management emissions (see SI 4). Crop AD achieves net mitigation of 29 to 114 kg CO_2 eq. per Mg of grass or maize, respectively (Figure 2). Alternative afforestation of land, instead of cultivation of crops for biogas production, would achieve 2.6 times (maize) to 11.5 times (grass) more net GHG mitigation, based on current yields of grass and maize (Lamb et al., 2016) – data not shown. Thus, whilst we do not account for the potential to sequester soil carbon via conversion of arable land to permanent grassland for AD feedstock supply, it is clear that this establishing trees would be a much more effective GHG mitigation option.

In the context of CCC's projections for 80% decarbonisation, prevention remains by some margin the most effective GHG mitigation option for food waste, supporting mitigation of up to 1,158 kg CO_2 eq. Mg^{-1} food waste owing to avoided food production, increasing up to 5,176 kg CO_2 eq. Mg^{-1} if spared grassland is afforested to sequester CO_2 from the atmosphere (Figure 3). In comparison, AD of food waste supports net mitigation of 183 kg CO_2 eq. Mg^{-1}, whilst using relevant fractions of that food waste as animal (pig) feed supports 337 kg CO_2 eq. Mg^{-1} – which would rise to 1,103 kg CO_2 eq. Mg^{-1} if spared arable land was afforested. Again, most captured manures are sent to AD in the CCC technology context. Mitigation is considerably lower than in the current technology context, ranging from 47 to 92 kg CO_2 eq. Mg^{-1}, reflecting a 50% reduction in manure management emissions owing to practices such as covered storage). Crop AD achieves net mitigation of 42 to 118 kg CO_2 eq. per Mg of grass or maize, respectively (Figure 3). Alternative afforestation of land, instead of growing crops for biofuel production, would achieve 50% to 340% more net GHG mitigation, based on future projected yields of grass and maize (Lamb et al., 2016). Almost half of the net GHG mitigation achieved by AD is attributable to Bioenergy crops with carbon capture and storage (BECCS), owing to a relatively low assumed GHG intensity of future (substituted) electricity (see SI B4); thus the GHG mitigation efficacy of AD could be significantly lower if the necessary technology for BECCS is not commercially viable and scalable in the near future.

The relative performance of AD in terms of GHG mitigation declines in the context of more ambitious net zero decarbonisation, as shown in Figure 4, owing to minor mitigation achieved via substitution of marginal electricity and heat generation and fertiliser production. Crop AD becomes completely ineffective as a GHG mitigation option, even after BECCS, achieving net mitigation of just 20 kg CO_2 eq. per Mg of maize and increasing GHG emissions by 20 kg CO_2 eq. per Mg of grass digested. Sending manures to AD in the net zero context results in relatively small mitigation of 27 to 57 kg CO_2 eq. Mg^{-1}, since the manure management emissions and fertiliser manufacture emissions, which AD avoids, are assumed to be lower in this scenario (SI B4). Food waste prevention remains the most important option to mitigate emissions, but mitigation reduces to 623 kg CO_2 eq. Mg^{-1} owing to the reduced GHG intensities of food production, approximately 50% lower than current intensities (SI B2). Afforestation of spared grassland would increase mitigation to 5,176 kg CO_2 eq. Mg^{-1} – also reduced relative to the other contexts owing to higher crop yields (lower land requirements, and thus less land spared for afforestation SI B2).

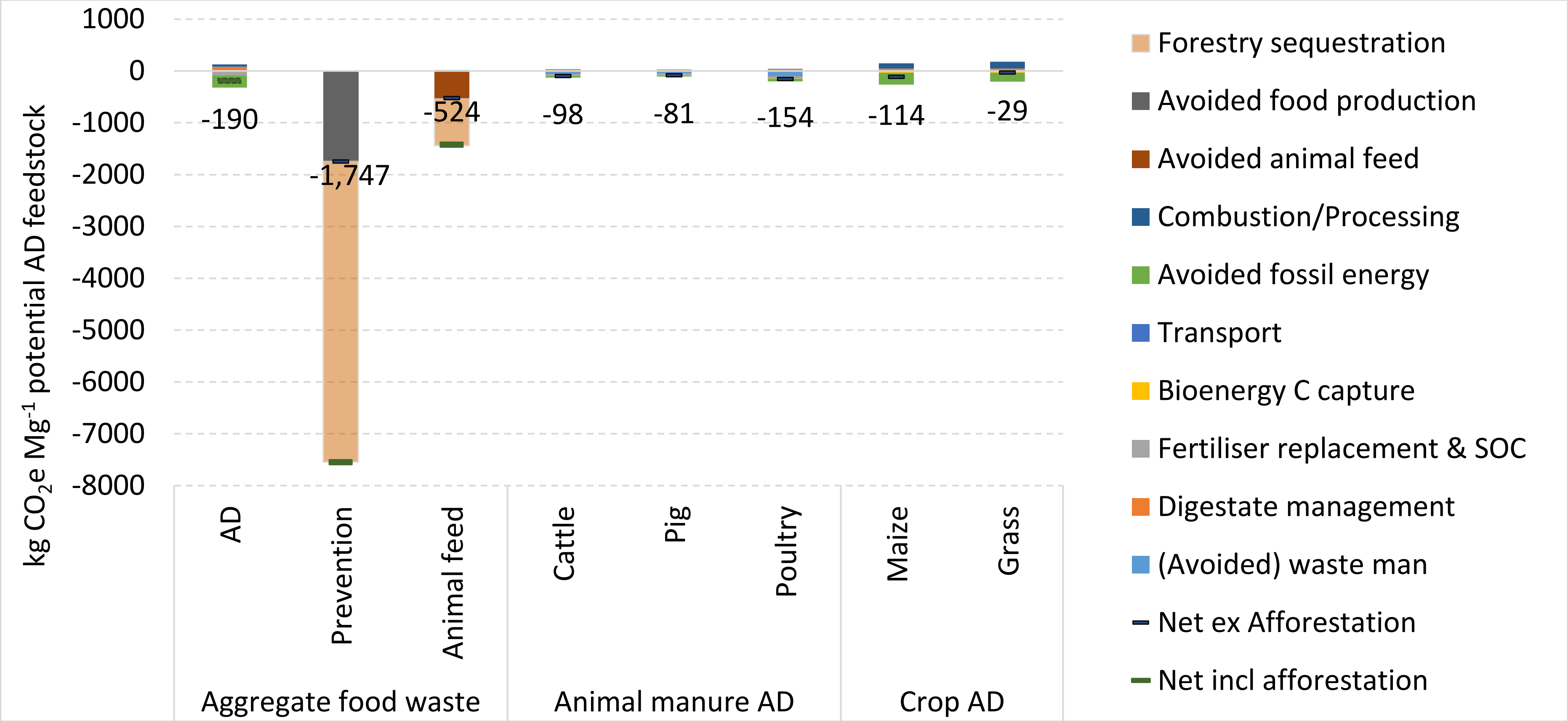

*Figure 3. Performance per Mg (tonne) of food waste (aggregated), manures, maize and grass undergoing different fates including composting, anaerobic digestion (AD), use as animal feed or prevention of waste arising **under current technology** (AD-Max scenario). For crop feedstocks to AD, alternative use of land for afforestation is considered. These results relate to current technology, and use of biomethane as a heating fuel distributed via the gas grid and as a transport fuel, replacing diesel.*

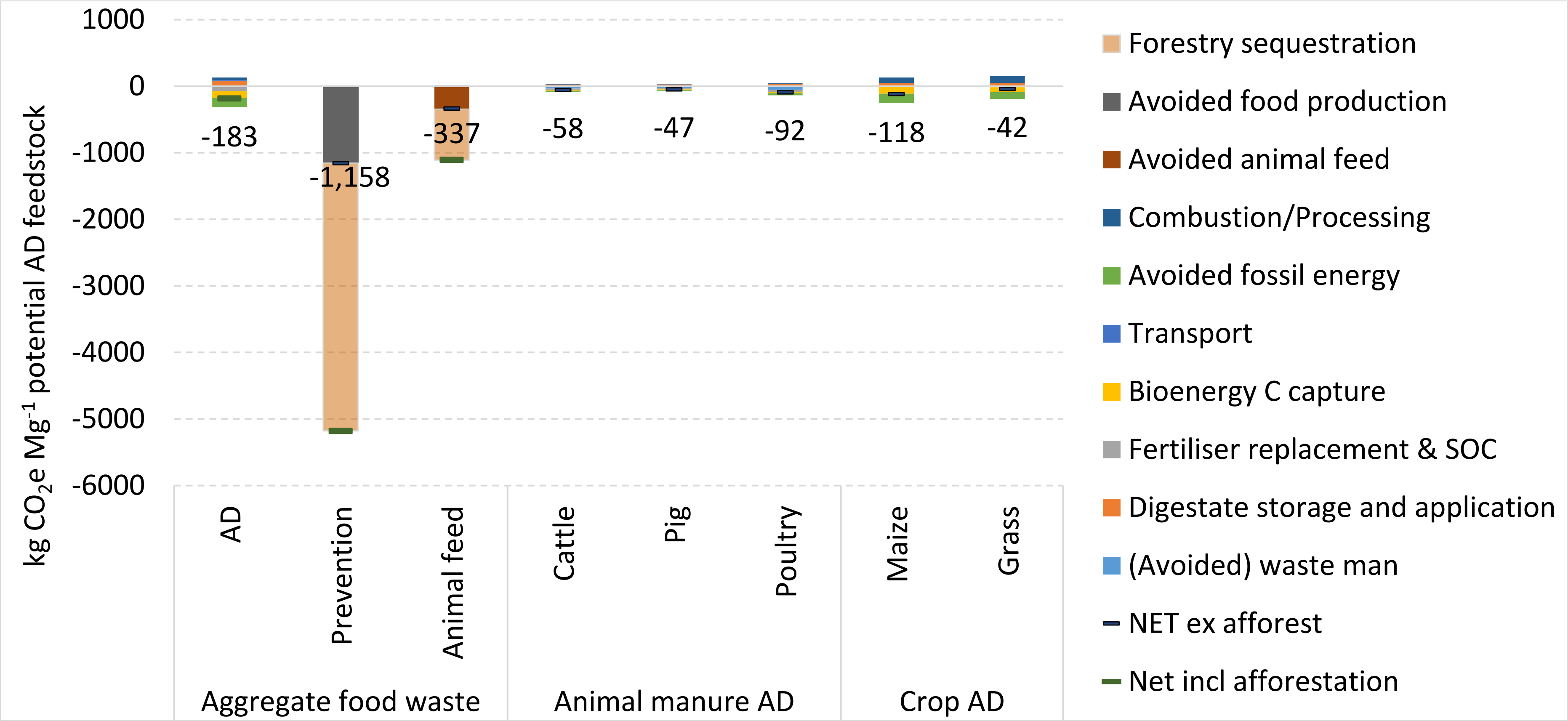

Figure 4. Performance per Mg (tonne) of food waste (aggregated), manures, maize and grass undergoing different fates including composting, anaerobic digestion (AD), use as animal feed or prevention of waste arising. For crop feedstocks to AD, alternative use of land for afforestation is considered. These results relate to ***CCC projection technology*** *(AD-Max scenario) and notably assume that bioenergy carbon capture & storage (BECCS) is applied to sequester 90% of the carbon in the 50% of biomethane combusted for electricity generation.*

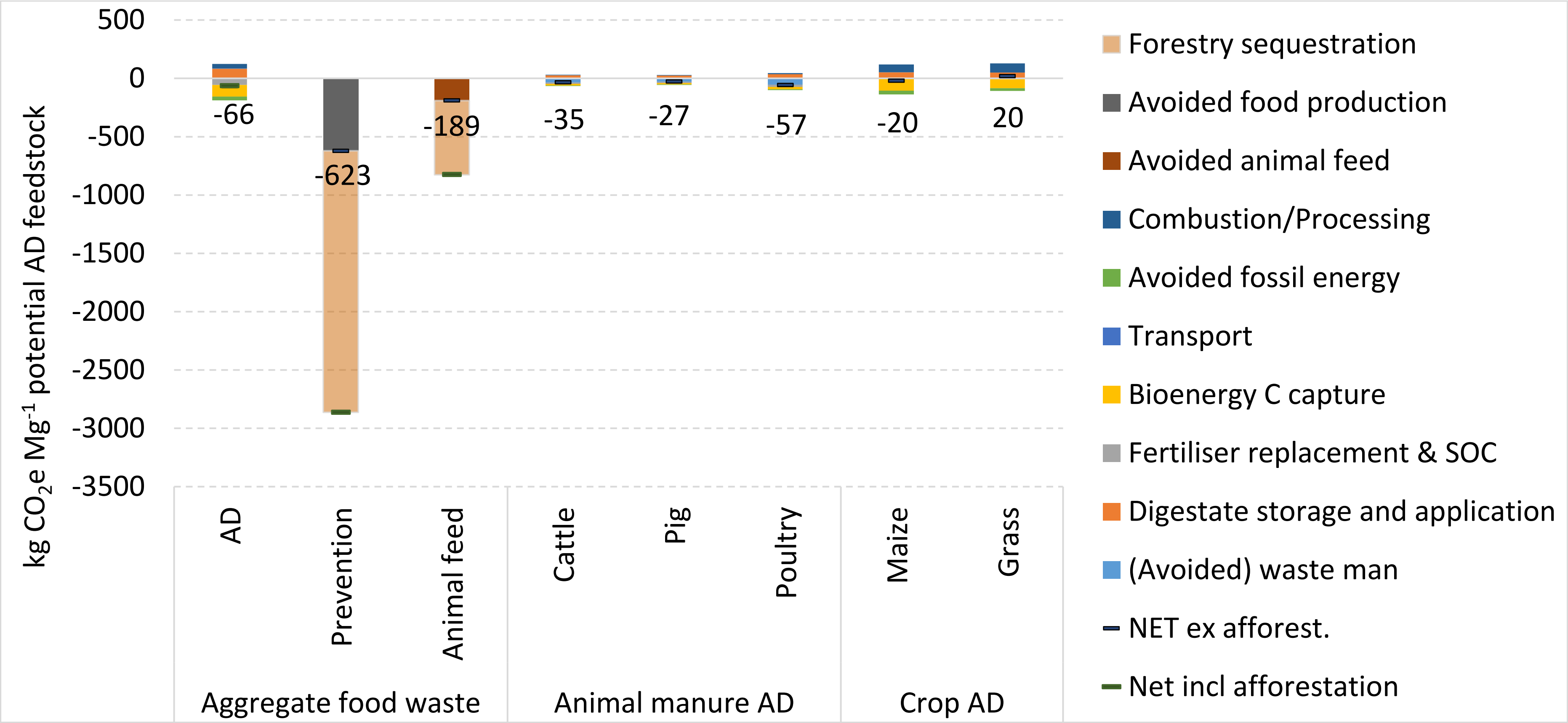

*Figure 5. Performance per Mg (tonne) of food waste (aggregated), manures, maize and grass undergoing different fates including composting, anaerobic digestion (AD), use as animal feed or prevention of waste arising. For crop feedstocks to AD, alternative use of land for afforestation is considered. These results relate to prevailing technology in a **Net Zero GHG future** (AD-Max scenario), and notably assume that bioenergy carbon capture & storage (BECCS) is applied to sequester 90% of the carbon in the 50% of biomethane combusted for electricity generation.*

National mitigation potential

Under current technology, AD-max could mitigate up to 34.4 million tonnes (Mt) yr^{-1} CO_2 eq. (Table 8), equivalent to 8% of UK GHG emissions in 2018 (BEIS, 2019) (Table 9). Of this mitigation, 14.9 Mt yr^{-1} CO_2 eq. is directly attributable to AD, and the majority of the remainder to prevention (Table 9 & Figure 5) – in particular to potential afforestation of spared land. In the Circular economy scenario, mitigation is doubled to 66.9 Mt yr^{-1} CO_2 eq. (Table 8), equivalent to 15% of UK GHG emissions in 2018 (BEIS, 2019), of which 13.3 Mt yr^{-1} CO_2 eq. is achieved by AD (Table 9). In the Circular economy scenario, mitigation is dominated by waste prevention, manure AD and afforestation of grassland no longer required for food production (which is responsible for circa 80% of the mitigation achieved by prevention - see SI A3).

Whilst mitigation in the above results is dominated by afforestation on spared land, the pattern of results (i.e. ranking of GHG mitigation efficacy) would look the same if potential afforestation on spared land is excluded. Meanwhile, potential alternative use of 319,000 ha of arable land spared from AD-cropping in the Circular vs AD-Max scenario (SI B5) for solar PV electricity generation results in a net additional 454,000 TJ yr^{-1} useful energy output. Solar PV generates 12-18 times more useful energy per hectare than maize or grass grown for AD (SI B5). The sum of AD plus solar PV energy generation in the Circular scenario equates to 9% of total UK energy consumption in 2018 (BEIS, 2019b). Alternative use of the 213,000 ha of arable land spared from animal feed production in the Circular scenario for cultivation of potatoes and peas could produce 24% of UK food energy requirement plus 25% of UK food protein requirement (British Nutrition Foundation, 2019). Equivalent values for the AD-Max scenario are 14% of energy and 15% of protein requirements (Table 8 and SI B5).

In a future context of substantial decarbonisation in line with UK CCC projections for 80% decarbonisation, food waste prevention alongside maximum AD deployment could generate substantial GHG mitigation of 23.3 Mt of CO_2 eq. (Table 8), equivalent to 12% of project UK GHG emissions in a context of 80% decarbonisation vs 1990 (CCC, 2019). However, just 10 Mt of this mitigation is specifically attributable to AD (Table 9) – the majority is accounted for by avoided food production and afforestation on spared land as a consequence of waste prevention (Figure 5, SI A3 and SI A5). More circular use of waste resources and land could nearly double this mitigation to 42.4 Mt CO_2 eq. yr^{-1} (equivalent to 22% of projected UK GHG emissions within an 80% decarbonisation context). Land areas spared are lower compared with the Current tech context owing to more land-efficient crop and livestock production (SI B2). Use of the 250,000 ha of arable land spared from AD cropping for solar PV electricity generation (SI B5) could increase net energy output to 464,000 TJ yr^{-1} in the Circular scenario, over four times the net useful energy generation in the AD-Max scenario (Table 8). Alternative use of the 182,000 ha of arable land spared from animal feed production in the Circular scenario (SI B5) for food security objectives could produce 18% of UK food energy requirement plus 19% of UK food protein requirement (British Nutrition Foundation, 2019). Equivalent values for the AD-Max scenario are 10% of energy and 11% of protein requirements (Table 8 and SI B5).

Table 8. Net GHG mitigation, energy generation from anaerobic digestion (AD) and potential solar photovoltaic electricity generation on spared land, and potential additional food production on spared land, for a scenario in which AD deployment is maximised and a scenario in which wastes are diverted to the highest value uses first (animal feed where possible) in accordance with circular economy principles.

Context	**Scenario**	**Land sparing**		**GHG mitigation Mg CO_2e yr^{-1}**	**Energy generation TJ yr^{-1}**	**Food security**	
		Arable (ha)	**Grass (ha)**			**Mcal yr^{-1}**	**Mg yr^{-1} protein**
Current tech	**AD-max**	4.62E+05	1.05E+06	-3.44E+07	1.13E+05	8.72E+09	2.53E+05
	Circular	1.16E+06	3.19E+06	-6.69E+07	5.67E+05	1.58E+10	4.58E+05
80% Decarb	**AD-max**	3.60E+05	7.25E+05	-2.33E+07	1.14E+05	6.79E+09	1.97E+05
	Circular	8.83E+05	2.22E+06	-4.24E+07	4.64E+05	1.20E+10	4.58E+05
NZC	**AD-max**	2.55E+05	4.04E+05	-1.05E+07	9.22E+04	4.82E+09	1.40E+05
	Circular	7.21E+05	1.27E+06	-2.22E+07	3.70E+05	8.00E+09	4.58E+05

Assuming more ambitious decarbonisation, to achieve NZC, net mitigation achieved by both AD-max and Circular scenarios is approximately halved, with the relative performance of the Circular scenario improving to more than double the net mitigation of the AD-Max scenario (Table 8). However, in the context of radical decarbonisation, the emissions avoidance and offset achieved by the Circular economy scenario equates to 27% of projected gross national emissions (Table 9), showing that food (waste) management will have a crucial role to play in curtailing future emissions when most economic activities have been largely decarbonised. The share of this mitigation achieved by AD, 2.8 Mt CO_2 eq. yr^{-1} (Table 9), is less than 10% of total mitigation arising from better management of food waste, indicating a diminishing role for AD if organic waste related emissions are to be strongly minimised, as required to meet Net Zero Carbon objectives. Total energy output from the Circular scenario is four times higher, food energy 65% higher and food protein over three times high than in the AD-Max scenario (Table 8).

Table 9. Summary of annual mitigation (negative emissions) across major processes in the AD-max and Circular scenarios, across the three decarbonisation contexts, with totals expressed in relation to gross UK emissions in each context

		Current Technology		80% decarbonisation		Net Zero Carbon	
		AD-Max	**Circular**	**AD-Max**	**Circular**	**AD-Max**	**Circular**
		Mg CO_2e yr^{-1}					
Food waste	**Prevention**	-4,158,366	-11,736,837	-2,757,407	-7,818,974	-1,482,316	-4,237,124
	Animal feed	-1,522,470	-1,823,508	-978,146	-1,171,741	-549,513	-653,927
	Insect feed	0	0	0	0	0	0
	AD	-1,755,928	-1,104,228	-1,691,743	-1,053,578	-608,750	-280,234
Industrial waste	**Animal feed**	0	-338,203	0	-217,321	0	-121,283
	Animal feed-insects	0	0	0	0	0	-476,203
	AD	-171,760	-84,827	-165,481	-80,936	-59,546	-30,826
Crop	**AD**	-908,136		-1,028,688	0	27,021	
Afforestation		-13,800,930	-39,727,604	-9,566,625	-24,961,574	-5,332,321	-13,913,278
Manure	**AD**	-12,107,158	-12,107,158	-7,137,337	-7,137,337	-2,470,196	-2,518,568
Manure	**Animal feed-insects**	0	0	0	0	0	-48,371
TOTAL		**-34,424,748**	**-66,922,366**	**-23,325,428**	**-42,441,461**	**-10,475,620**	**-22,279,813**
AD mitigation		-14,942,982	-13,296,214	-10,023,250	-8,271,852	-3,111,471	-2,829,628
% UK emissions		**-8%**	**-15%**	**-12%**	**-22%**	**-12%**	**-27%**
2018 UK GHG emissions		4.49E+08	4.49E+08				
80% reduction (vs 1990)				1.97E+08	1.97E+08		
Net Zero Carbon gross emissions						8.40E+07	8.40E+07

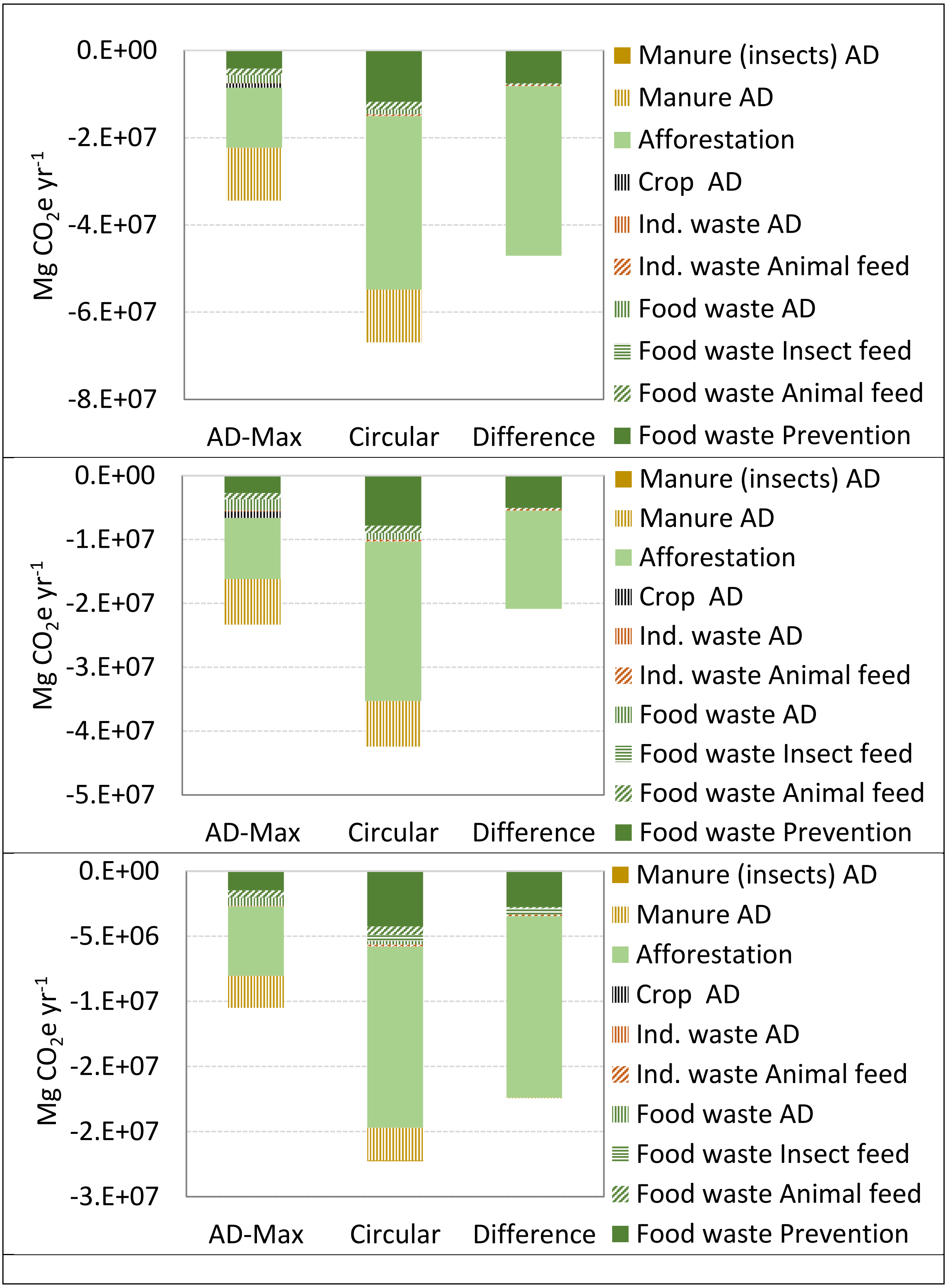

Figure 6. Net GHG mitigation achieved by diversion of food wastes, crops and manures into anaerobic digestion or animal feed in the AD-max and Circular scenarios within the context of current technology (top), or prevailing technology under 80% decarbonisation (middle) or meeting net zero carbon targets (bottom).

4. Conclusions

Anaerobic digestion (AD) is an environmentally efficient technology to manage genuine organic wastes, and has a role to play in the circular economy via renewable energy generation and cycling of nutrients. Despite large anticipated reductions in the GHG intensity of manure storage, energy generation and fertiliser use avoided or substituted by AD system flows, AD could contribute substantially to GHG mitigation in a net zero GHG future. Nonetheless, AD is not an efficient energy generating technology, and waste management is always less efficient than waste prevention. Extrapolation of current trajectories of AD deployment to a future AD-max scenario in the UK indicates that "excess" AD deployment could constrain waste prevention and higher value uses of waste for animal feed, whilst also appropriating arable land to cultivate crops for AD energy generation. Comparing potential maximum deployment of AD with a Circular scenario that minimises waste generation, and maximises diversion of non-human-edible potential waste streams into animal feed (via heat treatment and insects, accompanied by regulatory change), indicates that caution is required when deploying AD.

The Circular scenario achieved twice as much GHG mitigation as the AD-max scenario, ranging from 66.9 to 22.3 Mt CO_2 eq. under decarbonisation contexts ranging from Current Technology to Net Zero Carbon. Meanwhile, the AD-max scenario realised GHG mitigation ranging from 34.4 to 10.5 Mt CO_2 eq. as the wider economy decarbonised. The circular scenario could also support four times more energy generation, if land not required for energy crop cultivation is instead dedicated to electricity generation via solar PV, and three times more food protein production on land spared from animal feed production.

This analysis was based on an expanded boundary life cycle assessment of stylised (extreme) scenarios, taking the same hypothetical baseline of zero burdens from counterfactual management of food waste. It assumed that in future all behavioural and technical challenges to full separation of food waste from residual waste streams, along with safety and regulatory barriers to diversion of many food waste streams to animal feed, could be overcome. Whilst it is likely that the impetus towards net zero GHG emissions and a circular economy will steer waste management in this direction, these assumptions are not likely to be fully realised. Nonetheless, these assumptions enabled a clear comparison of two distinct policy pathways in terms of climate, food and energy security objectives. Results robustly support the following conclusions:

- AD will remain an efficient form of management for genuine organic wastes that supports net GHG mitigation even in a net zero carbon future when alternative energy and nutrient supplies have been heavily decarbonised.
- However, waste prevention and diversion of food waste to animal feed will remain far superior options to AD in terms of GHG mitigation and food security, even before land sparing is taken into account. In fact, food production is not expected to decarbonise to the same extent as energy generation, increasing the comparative advantage of prevention and animal feed diversion over AD.
- GHG mitigation via food waste prevention can be increased by up to five-fold if grassland spared from food production is afforested. This effect will remain dominant through time,

though could be reduced by two thirds owing to projected intensification of livestock food systems.

- Use of land for AD-cropping is highly inefficient in terms of GHG mitigation and energy security. Using land for solar PV generation instead of AD could support up to 18 times more energy generation per hectare under typical UK conditions.
- Constraining AD to organic waste fractions that cannot be prevented or diverted to higher value uses, and efficiently utilising all spared land for forestry, renewable energy and food production, could increase GHG mitigation by two-fold, energy generation by four-fold and food protein supply by three-fold compared with more indiscriminate maximum deployment of AD in line with industry projections.

5. Appendix

Food waste characterisation

The AD Max scenario was based on WRAP's modelling of how much food would go to different destinations in the future under the UK's current voluntary agreements. Broadly, these aim for 50% reductions in *post-farmgate edible* food waste against baselines set from *2007 onwards*, with some more limited reductions in primary production food waste:

- **Primary production:** Since primary production food waste is currently not included in the UK's national food waste reduction targets due to lack of robust data, it was assumed that a relatively conservative 10% of food waste and 5% of food surplus is prevented, the same volume goes to animal feed, and the remainder is split equally between AD and compost.
- **Manufacturing:** WRAP's estimations of how much additional food waste and surplus could go to higher stages in the food waste hierarchy by 2025 were used, broken down by individual product categories (WRAP, 2016). It was then assumed that an extra 41% of food waste goes to prevention and animal feed between 2025-30 compared with increases between 2015-25, to bring WRAP's projections up to 2030. Finally, to bring the figures in line with WRAP's restated figures for manufacturing level food waste in 2015, which were slightly higher volumes ("WRAP restates UK food waste figures to support united global action," 2018), food waste and surplus going to all destinations were increased by roughly 5.8% uniformly.
- **Retail:** WRAP's sector-wide projections for total food waste and surplus which would go to different stages of the food waste hierarchy by 2025 were used (WRAP, 2016). Since product-level breakdowns were not available for this sector, it was assumed that prevention occurred equally across product types. Since under current law, many types of food cannot go to animal feed, extra food diverted to animal feed was assumed to be the same composition as for the manufacturing sector in terms of product categories (e.g. mainly Bakery and Fresh Produce). It was then assumed that an extra 41% of food waste goes to prevention and animal feed between 2025-30 compared with increases between 2015-25, to bring WRAP's projections up to 2030. Finally, to bring the figures in line with WRAP's restated figures for manufacturing level food waste in 2015, which were slightly higher volumes ("WRAP restates UK food waste figures to support united global action," 2018), we increased food waste and surplus going to anaerobic digestion to account for the difference (it was assumed that no extra food would be prevented, as overall prevention was already very high for retail level).
- **Catering (Hospitality and food service):** Estimates for 2015 levels of food waste in hospitality and food service sector were taken from the breakdown by food category available given in a 2013 report (WRAP, Parfitt, Eatherley, Prowse, & Hawkins, 2013) and scaling up the food waste quantities uniformly based on WRAP's restated figures for food waste arising in 2015 for the overall sector ("WRAP restates UK food waste figures to

support united global action," 2018). WRAP has set targets to reduce food waste in hospitality and food service outlets by 100,000 tonnes by 2025 ("Guardians of Grub crusade to beat food waste," 2019). It was then assumed that an extra 41% of food waste goes to prevention between 2025-30 compared with increases between 2015-25, to bring WRAP's projections up to 2030 – assuming uniform prevention across food categories. The law was assumed to remain the same in this scenario, so that sending food waste from hospitality and food service to animal feed was illegal. Remaining food waste was assumed to be sent to Anaerobic Digestion.

- **Household:** WRAP projections for total reductions at household level by 2030 could not be found in their literature, so projections were extrapolated by taking WRAP's overall predictions for how much UK post-farmgate food waste would be reduced by 2030 – a 2.1 million tonne reduction (WRAP, 2019a)[3]. The total tonnes of food prevented or sent to animal feed in the other stages of the supply chain was subtracted from this overall reduction, to discover the remaining reductions required from the household stage. This required a reduction of approximately 1.5 million tonnes of food waste at household level, about a 21% reduction compared to 2015 levels. The law was assumed to remain the same in this scenario, so that sending food waste from households to animal feed was illegal – therefore all reduction was assumed to come from prevention. Remaining food waste was sent to Anaerobic Digestion.

The AD Max scenario was based on calculations of overall 50% reductions in *edible and inedible* food waste between 2015 and 2030, across the whole supply chain including primary production, using *2015 as a baseline* for reductions, and also assuming some prevention of food surplus currently going to animal feed:

- **Primary production:** It was assumed that 40% of food waste was prevented and 10% was diverted to animal feed, with the rest ploughed back into the field or sent to AD. It was assumed that 50% of food surplus was prevented for fruit and vegetables, and 20% of food surplus was prevented for other food categories. The remainder of food surplus was assumed to be sent to animal feed, and the remainder of food waste to be sent to anaerobic digestion.
- **Manufacturing:** It was assumed that 35% of food waste was prevented, 15% was diverted to animal feed, and 50% was sent to AD. It was assumed that 100% of food surplus currently redistributed is prevented, 30% of food surplus currently going to animal feed is prevented, and the remainder of food surplus still goes to animal feed.
- **Retail:** WRAP's disaggregated figures for retail level food waste (WRAP, 2016) were updated in line with WRAP's restated 2015 statistics for retail (WRAP, 2018a), assuming uniform increase in all food categories. The same level of food surplus was assumed as in the 2016 report as these figures were not restated. This scenario assumed that 40% of current food waste was prevented, 10% was diverted to animal feed, and the remaining 50% was sent to

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[3] Since these calculations were performed, WRAP have since slightly upgraded their ambition from 2.1 million tonnes reduction to 2.5 million tonnes reduction.

AD. It assumed that 100% of food surplus currently redistributed is prevented, 30% of food surplus currently going to animal feed is prevented, and the remainder of food surplus is still diverted to animal feed. It was assumed that the law had been changed in this scenario to allow food containing meat to be sent to animal feed after processing.

- **Catering (Hospitality and food service):** WRAP's disaggregated figures for hospitality and food service level food waste (WRAP et al., 2013) were updated in line with WRAP's restated 2015 statistics for hospitality and food service (WRAP, 2018a), assuming uniform increase in all food categories. It was assumed that 35% of current food waste was prevented, 15% was diverted to animal feed, and the remaining 50% was sent to AD. It should be noted that the law is assumed to change in this context to allow food waste from catering to be diverted to animal feed, after processing.
- **Household:** WRAP's disaggregated figures for household level food waste (WRAP, 2018b) were updated in line with WRAP's restated 2015 statistics for hospitality and food service (WRAP, 2018a), assuming uniform increase in all food categories. It was assumed that 50% of current food waste was prevented, with 85% coming from edible food waste, and 15% coming from inedible food waste – with the remainder of food waste assumed to be sent to AD. It is assumed that it will not be possible to send food waste from household level directly to animal feed even if the law changes to allow food waste from catering and containing meat to be diverted to animal feed after safe treatment, because segregation of food waste is too difficult to regulate to ensure non-food toxic items do not make their way into this waste stream. However, in the Net Zero context, it is additionally assumed that 50% of the remaining food waste sent to AD is instead sent to animal feed via insects.

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[i] This does not include water treatment facilities or those treating sewage sludge.

[ii] The biggest projected growth comes from animal wastes and bedding feedstocks, which currently account for less AD energy generation than crops or food waste, but the industry also predicts strong potential growth in crops as AD feedstocks, despite the literature recently questioning the sustainability of crops to AD.

[iii] If renewable energy was used for animal feed processing, feed (including dry-feed) could potentially beat biogas and compost on all indicators.

[iv] The one exception in this study was fruit and vegetable waste – for which sending it to AD resulted in lower emissions than sending it to animal feed. However, sending food to human consumption was always preferable to sending it to AD for all products.

[v] With some notable exceptions – for instance, Fusi *et al.* (2016) conclude that hydro, wind, and geothermal power are better alternatives to biogas electricity.