GREEN GAS WITHOUT THE HOT AIR

Defining the true role of biogas in a net zero future

FEED BACK

Front cover image: Biogas Plant.
Credit: LianeM, Shutterstock

DISCLAIMER

Feedback takes the greatest possible care in collecting information and drafting publications but cannot guarantee that this report is complete. It relies heavily on secondary sources, which are reproduced here in good faith. Feedback assumes no responsibility for errors in the sources used and makes no claim that any named financial institution knowingly finances any wrongdoing or is guilty of any breach of policy, or that any named business has committed any wrongdoing.

CONTENTS

GLOSSARY

AD — ***Anaerobic digestion***
A natural process whereby plant and animal materials (biomass) are broken down by micro-organisms in the absence of air, producing a methane-rich gas and digestate.

ADBA — ***Anaerobic Digestion & Bioresources Association***
UK-based trade association for anaerobic digestion and associated industries.

AFSB — ***Agri-Food Strategy Board***
An industry-led committee formed by the government of Northern Ireland to create a strategic action plan for agriculture.

BECCS — ***Bioenergy with carbon capture and storage***
The process of extracting bioenergy from biomass and capturing and storing the carbon.

BEIS — ***Department for Business, Energy & Industrial Strategy***
UK government department, with responsibility for business, industrial strategy, science and innovation, energy and climate change policy.

CCC — ***Committee on Climate Change***
An independent public body formed to advise the United Kingdom and devolved Governments and Parliaments on tackling and preparing for climate change.

CCS — ***Carbon capture and storage***
The process of capturing and storing carbon dioxide before it is released into the atmosphere.

CfD — ***Contracts for Difference (CfD)***
UK Government subsidies for large-scale (over 5 MW) electricity generation from renewable sources.

CO_2eq — ***Carbon dioxide equivalent***
A metric measure used to compare the emissions from various greenhouse gases by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential.

CHP — ***Combined heat and power***
Process that captures and utilises the heat that is a by-product of the electricity generation process.

DAERA — ***Department of Agriculture, Environment and Rural Affairs***
Government department of the Northern Ireland Executive, with responsibility for agriculture, environment and rural affairs.

Energy crop
Crop grown for the purpose of being converted into energy rather than for human consumption.

Energy livestock
Farming where manure or slurries are supplied as feedstocks for AD – through reducing the industry's waste disposal costs, locking in demand for manure and slurries, and helping farms gain planning permission, AD thus forms part of a symbiotic relationship that supports the continuation of an environmentally destructive industry.

GHG — ***Greenhouse gas***
Any gas that has the property of absorbing infrared radiation emitted from Earth's surface and reradiating it back to Earth's surface, thus contributing to the greenhouse effect.

GW — ***Gigawatt***
A unit of power, equal to one billion watts.

HGV — ***Heavy goods vehicle***
A large, heavy motor vehicle used for transporting cargo.

IPCC — ***Intergovernmental Panel on Climate Change***
The United Nations body for assessing the science related to climate change.

kWth — ***Kilowatt-thermal***
A unit of heat-supply capacity used to measure the potential output from a heating plant.

LCA — ***Life cycle assessment***
A life cycle assessment 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.

M ha — ***Mega hectare***
A unit of area, equal to one million hectares.

Mt — ***Megatonne***
A unit of mass, equal to one million metric tons.

MW — ***Megawatt***
A unit of power, equal to one million watts.

MWh — ***Megawatt hour***
One million watts of electrical power used over the period of 1 hour.

NDCs — **Nationally determined contributions**
The voluntary pledges to reduce national carbon emissions, which nation states adopt at the UN Framework Convention on Climate Change Conference of the Parties (COP).

Net zero — ***Net zero emissions***
Achieving an overall balance between emissions produced and emissions taken out of the atmosphere, such that the emissions produced are cancelled out. In practice, this is realistically primarily driven by a gross reduction in emissions, complemented by some carbon sequestration.

NFU — ***National Farmers' Union***
The largest union representing farmers in the UK.

NVZ — ***Nitrate vulnerable zone***
Areas designated as being at risk from agricultural nitrate pollution

RTFC — ***Renewable transport fuel certificate***
Certificates issued by the UK government to fuel suppliers, who then use these to demonstrate that they are meeting their obligations to provide a percentage of their fuels from renewable sources under the RTFO.

RTFO — ***Renewable transport fuel obligation***
A legal requirement for suppliers of transport and non road mobile machinery fuel in the UK to show that a percentage of the fuel they supply comes from renewable and sustainable sources.

RHI — ***Renewable heat incentive***
UK Government subsidies encouraging the uptake of renewable heat technologies amongst householders, communities and businesses – including AD used to produce biogas or biomethane.

SRC — ***Short-rotation coppice***
An energy crop of densely planted, high-yielding trees (typically poplar or willow), which are typically cut back every 2 – 4 years to promote the growth of multiple stems.

SRF — ***Short-rotation forestry***
An energy crop of densely planted, high-yielding trees (typically poplar or willow), which are typically harvested every 8 – 20 years once the trees have reached 10-20 cm diameter at breast height.

Solar PV — ***Solar photovoltaic***
A specific type of solar power generation based on the photovoltaic effect – photons strike a surface of a specially made material that causes the release of electrons. Other types of solar energy include solar thermal, which uses sunlight to boil a fluid.

SDG — ***Sustainable Development Goal***
The SDGs are a collection of 17 global goals to be achieved by 2030, set in 2015 by the United Nations General Assembly and addressing poverty, inequality, climate change, environmental degradation, peace and justice.

TJ — ***Terajoule***
A unit of energy, equal to one trillion joules.

TWh — ***Terawatt-hour***
A unit of electrical energy, equal to one trillion watt-hours.

UNFCCC — ***UN Framework Convention on Climate Change***
The largest international environmental treaty aimed at reducing global greenhouse gas emissions to avert climate change.

WBA — ***World Biogas Association***
The global trade association for the biogas, landfill gas and anaerobic digestion (AD) sectors.

WRAP — ***Waste and Resources Action Programme***
A British registered charity which works with businesses, individuals and communities to achieve a circular economy. It facilitates the UK's main voluntary food waste reduction agreements.

EXECUTIVE SUMMARY

As countries and companies commit to net zero greenhouse gas (GHG) targets of varying ambition, anaerobic digestion (AD) has been framed as an environmental silver bullet, a form of renewable energy to rival wind and solar in its desirability and environmental credentials. AD is the process of taking organic materials, known as 'feedstocks', both purpose-grown, like maize and other crops, and waste streams, like food waste and manure, and breaking them down using micro-organisms in the absence of air. This produces methane-rich biogas, which can be used to generate heat or electricity, and nutrient-rich digestate, which can be used as a fertiliser. In the UK, the AD industry portrays itself as both a panacea for difficult-to-decarbonise sectors like heating and transport – by providing a sustainable source of power – and a solution to organic waste management – for multiple sectors from livestock farming to retail. At conferences with titles like *There's No Net Zero Without Biogas* (ADBA, 2019b), the industry argues that the AD and biogas sector is already cutting UK emissions by 1% annually, and has the potential to reduce emissions by 6% (Whitlock, 2019). This report takes a detailed look at whether the reality of AD can fulfil these promises in the context of an ambitious net zero future.

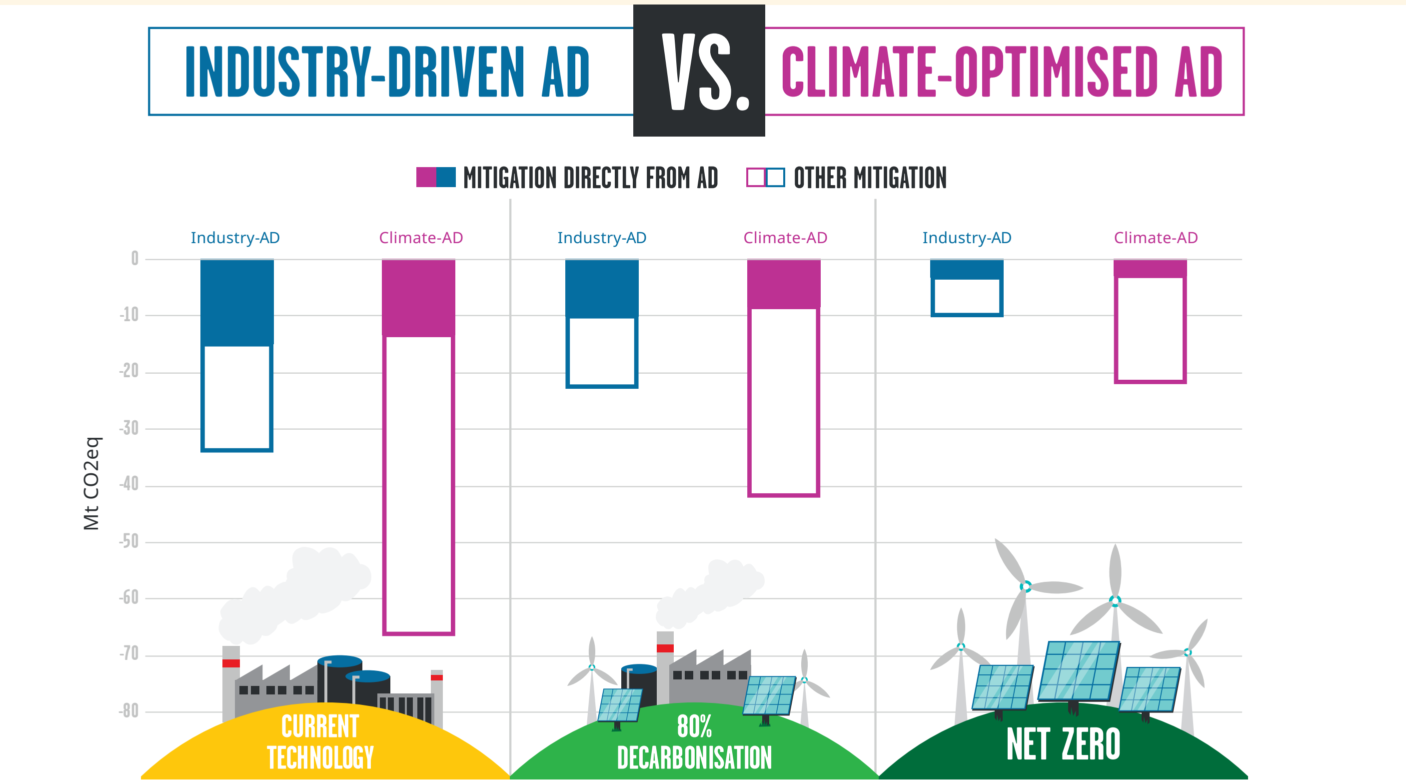
In the early to mid-2010s, AD was generously subsidised, making it a lucrative industry which grew significantly. Many finance companies, some of them based in tax havens, have generated significant profits from AD, largely as a result of subsidies. As subsidies have declined, the growth of the sector has recently stalled, but the AD industry still hopes to grow to 16–30 times its current size by 2032 (ADBA, 2018, p. 15), which would mean building around 100 new AD plants every year (WRAP, 2019a). More AD plants mean more feedstock inputs, and along this path to growth, the industry would increase its use of food waste, roughly double its use of crops, and more than triple its use of animal manures and slurries (ADBA, 2018, p. 16). To reach its goals, the AD industry is lobbying for the government to renew and increase subsidies to ensure it can compete with cheaper green energy alternatives like solar and wind. Key to the AD industry's sustainability claims are comparisons between AD and environmentally damaging alternatives for both energy generation and waste disposal, such as petrol and natural gas, landfill and open storage of manure. AD compares favourably to these options – presenting AD as the only alternative to 'unavoidable' waste streams and 'hard-to-decarbonise' sectors.

To date, the AD industry's claims have largely gone unchallenged. However, by comparing the AD industry's ideal scenario – one that maximises growth and draws the greatest subsidies – with a scenario in which policy decisions maximise proven climate change mitigation policies, this report shows that the benefits of AD have been overstated. Worse, the industry's ambitions may be crowding out better environmental alternatives. This report uses the results of a life cycle assessment (LCA) conducted in collaboration with researchers at Bangor University to shed some much-needed light on the limitations of AD, and show what role there is (and is not) for AD in a sustainable future.

We used two scenarios to build our LCA. In the first scenario – 'industry-driven AD' – the volume of feedstocks processed by AD is maximised roughly in line with the industry's growth ambitions, alongside some limited food waste prevention.

In the second scenario – 'climate-optimised AD' – fewer feedstocks are sent to AD, and sustainable alternatives to AD are prioritised instead, such as scaling up food waste prevention, afforestation of land, planting food for human consumption, and building solar photovoltaic (solar PV). These two scenarios were modelled in three contexts – our current context in terms of energy mix and land use, a context in which the UK economy was 80% decarbonised, and a net zero context (for more detail on our LCA modelling, see Section 4).

The results are startling.



In the current context, the climate-optimised AD scenario achieves roughly twice the emissions mitigation of the industry-driven AD scenario. It also produces enough additional solar PV energy output to meet 8% of current UK energy consumption, and enough extra food production to feed 8.6 million more people annually (13% of the UK population). The value of AD for emissions mitigation dwindles as the UK economy decarbonises and more environmentally friendly forms of renewable energy become dominant. **By the time the UK reaches our net zero context, the climate-optimised AD scenario would still achieve over twice the emissions mitigation compared with the industry-driven scenario.**

Our key findings and recommendations across four climate policy issue areas are set out below.

ENERGY GENERATION – ELECTRICITY AND GAS

Wind, solar and other renewables produce far lower emissions and are generally lower cost than AD, so the case for AD has usually rested on it providing biomethane ('green gas') for sectors that are more difficult to decarbonise – like gas heating and heavy goods vehicles (HGVs). Here too, there may be alternatives: it is important to carefully weigh up whether investments in faster and more comprehensive electrification of transport and heating systems might be preferable to sinking money into expensive biomethane-reliant infrastructure, locking in demand for AD feedstock long into the future (with many subsidies currently guaranteed over periods of up to 20 years).

Priorities such as building greater infrastructure for electric cars and converting heating systems to be run on electricity (for example, through heat pumps) may be more prudent long-term investments than investing in AD plants. For instance, there has been encouraging research into how even heavy freight vehicles could be electrified by the 2030s (Ainalis, Thorne and Cebon, 2020), one the sectors the AD industry has been keen to portray as difficult to electrify.

We recommend that renewable electricity subsidies are not given to AD, and support is instead directed to rapidly upscaling more efficient modes of production like wind and solar, plus energy storage solutions like batteries. For instance, AD should be excluded from Contracts for Difference (CfD) subsidies – but onshore wind and solar should be included, with levels of subsidy support increased for these technologies. We recommend that further comparative research is conducted into the relative economics and sustainability of prioritising biomethane or electrification of heat and transport systems.

Credit: Liane M

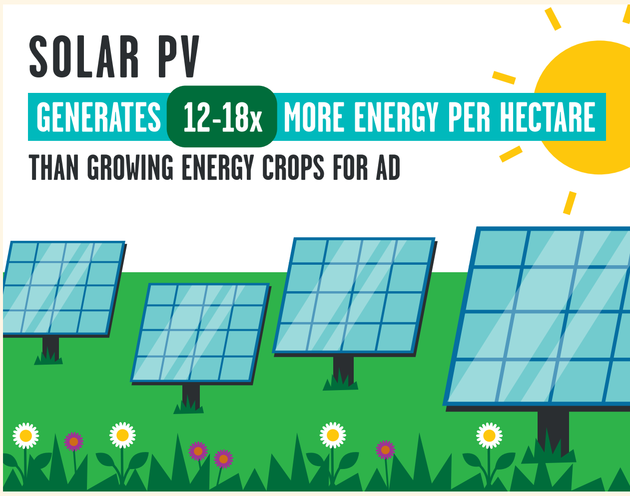
CROPS – PRIORITISING NUTRITION AND ENVIRONMENTAL REGENERATION

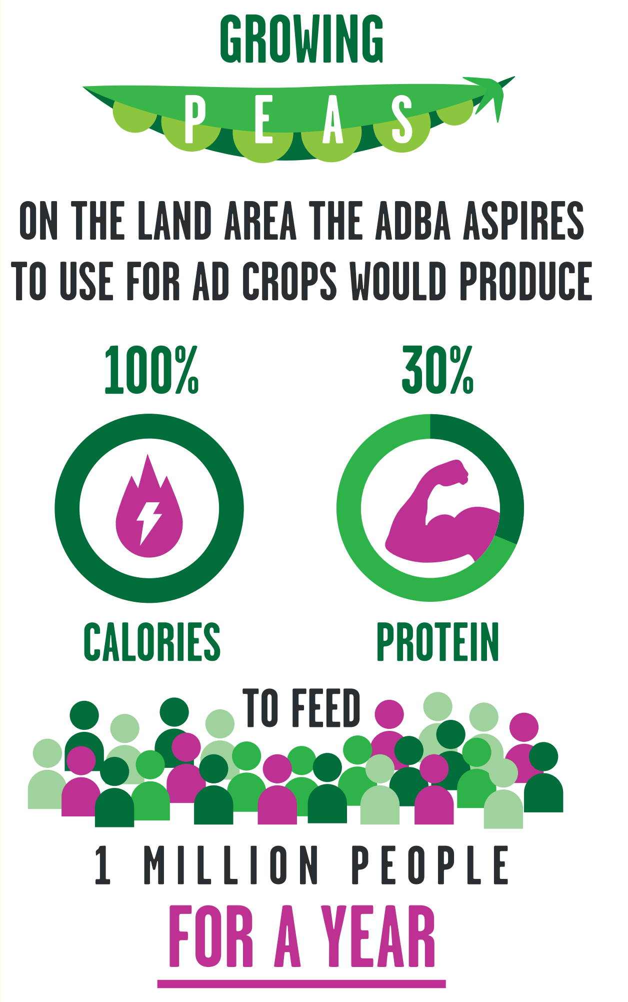
Even in our current energy and land use context, there are many better uses of land than 'bioenergy' crops like maize and grass. We found that **solar PV generates 12–18 times more energy per hectare than maize or grass grown for AD**. Alternatively, growing forests on land currently used to grow AD feedstocks would achieve between 2.6 times (vs maize biogas) and 11.5 times (vs grass biogas) more net GHG mitigation.

As the UK decarbonises, the emissions savings from growing crops for AD diminish even further. **By the time the UK reaches net zero, crop-based AD feedstocks become completely ineffective in emissions mitigation**, even assuming carbon capture and storage (an as yet unproven technology) is deployed at AD plants. In this context, grass AD feedstocks even become a net **producer** of emissions.

Currently, the crop most commonly grown for AD is maize, which is one of the most damaging crops for soils and uses valuable agricultural land which could be used for food production. **Beans, pulses and vining peas would be excellent candidates to replace maize when grown in rotation** – these would have a far better impact on soil quality, contribute to the UK's food security and assist the UK's transition to more plant-based proteins. If peas were grown for human consumption on the land area the ADBA aspires to use for AD crops, this would produce enough food for over 1 million people – 100% of their recommended calories per year, including roughly 30% of their recommended protein for a year. Oilseed rape is another alternative. Growing maize or grass as AD feedstocks has no role in a sustainable food system – whether the aim is energy generation, emissions mitigation or food security, far better alternatives are available.

We recommend that policy measures disincentivise maize and grass crops being used for AD – including removing subsidies for growing maize and grass as energy crops, and renewable heat incentive (RHI) subsidies for AD facilities using primarily crops. Potential future candidates for AD feedstocks should be rigorously evaluated to determine their sustainability and economic viability, as this is currently highly uncertain.





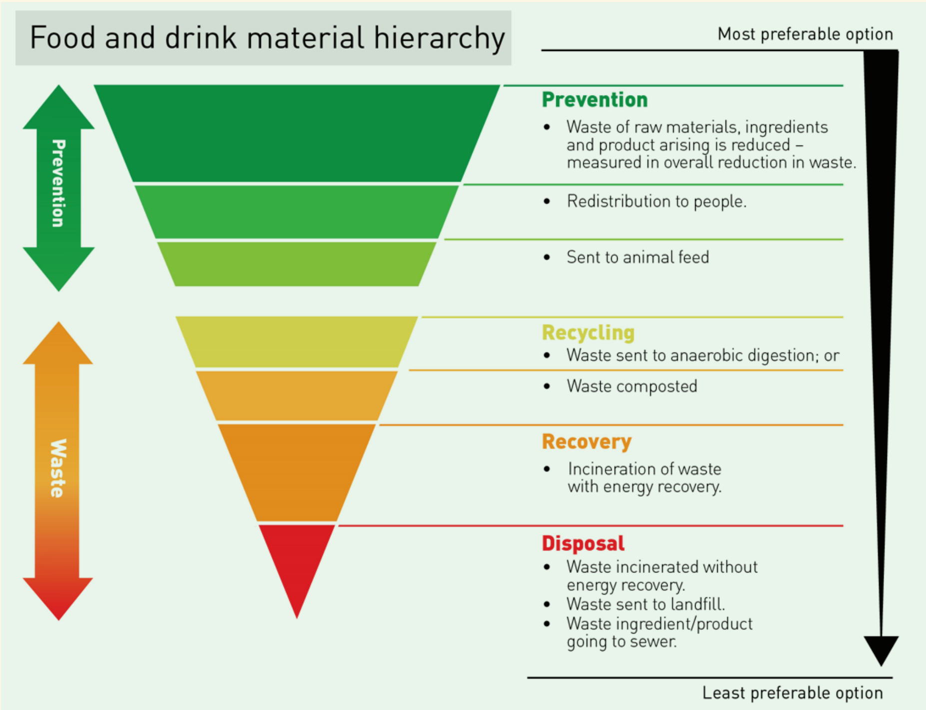
FOOD WASTE – A 'PREVENTION-FIRST' APPROACH

In the current context, preventing food waste results in direct emissions savings **over nine times higher than sending food waste to AD** (per tonne of food waste). If the grassland used to produce the meat and dairy that ends up as waste is instead afforested, emissions savings are **on average 40 times higher than sending the same volume of food waste to AD**, with spared cropland from other types of food waste also available to grow considerable volumes of food[1]. This means that preventing one tonne of food waste is environmentally equivalent to sending between 9 and 40 tonnes of food waste to AD.

1 In practice, most of the grassland saved in this way comes from the prevention of beef, lamb and milk waste – so reducing these types of food waste could result in far higher emissions mitigation per tonne saved. Foods grown on cropland would produce less or no extra emissions mitigation (unless trees were planted on former cropland) but could be used for considerable extra crop production to improve the UK's food security.

Prevention performs even better relative to AD in a net zero context. **Using food waste as animal feed saves nearly three times more emissions than sending it to AD** – and also saves significant areas of cropland for food production. Therefore, only unavoidable food waste that is inedible to humans or animals should be sent to AD, in line with the food waste hierarchy.

Figure 1: Food and drink material hierarchy

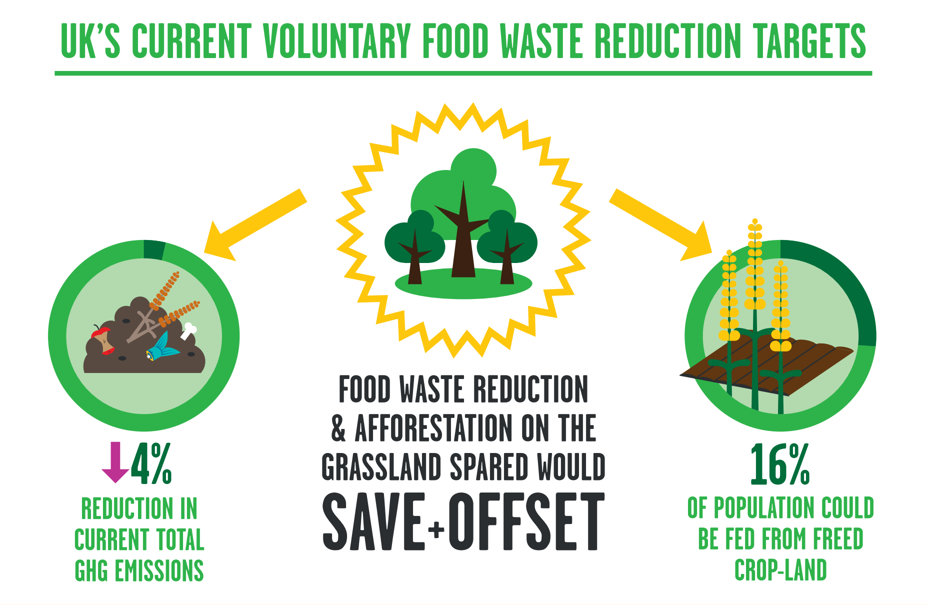


(WRAP, 2019b, p. 3)

AD is often used as a sticking plaster in place of the political ambition or imagination to achieve more fundamental change. **One of our LCA's most striking findings was that under the 'climate-optimised AD' scenario, halving UK food waste, with afforestation on the roughly 3 million hectares of grassland spared, would save and offset approximately 51 million tonnes CO_2eq – about 11.3% of the UK's current total GHG emissions. In**

addition, it would save 800,000 hectares of cropland which could produce 6.5 billion kcal per year more than the 'industry-driven AD' scenario – enough to feed 7.9 million people, nearly 10% of the UK population[2].

This scenario assumes an ambitious but achievable goal of halving UK food waste, in line with Sustainable Development Goal (SDG) 12.3, adopted by the UK in 2015, facilitated by greater regulation of food businesses. The scenario is significantly more ambitious than the pace of change currently set by the UK's voluntary food waste agreements – which would yield (at most) 63% lower emissions mitigation. In contrast, even in our most ambitious modelling for AD, **the maximum emissions mitigation attributable to AD is 3.3% of the UK's 2018 emissions**.



(The UK's current voluntary food waste targets aim to halve edible food waste only, using a baseline of 2007 onwards and excluding primary production from concrete targets. An ambitious regulatory target aims for 50% reduction of all food waste (in practice, a greater than 50% reduction of edible food waste) from farm to fork against 2015 baselines.)

2 This would decline in future decarbonisation contexts, but still be substantial.

This report finds that far from only dealing with 'unavoidable waste', when AD subsidies are set very high, as the AD industry is calling for, AD can actively hinder waste prevention, particularly when paired with a lack of regulation and funding for the better alternatives. Companies and redistribution charities have reported that edible food can be diverted down the food waste hierarchy to AD when incentives are skewed towards AD, hindering prevention efforts. Government funding for food waste prevention has been cut over the last decade, while AD has been heavily subsidised.

Credit: Feedback

We recommend that the government makes funding for food waste prevention a top climate priority. Being eaten by people is, by a considerable margin, the environmentally optimal destination for food. Where this is not possible, the next priority should be sending food to animal feed. Fiscal policy, like subsidies, taxes and penalties, should be structured to ensure that it makes more economic sense to prevent food waste or send surplus food to animal feed in preference to AD, in line with the food use hierarchy. In addition, taxes on landfill and incineration should be increased so that AD is incentivised as a last-resort option, with the revenue raised used to fund greater food waste measurement and prevention. Regulations should be introduced to go beyond the pace of change set by voluntary agreements and achieve 50% reductions in all food waste from farm to fork by 2030, against 2015 baselines.

MANURE AND SLURRIES – DISINCENTIVISING INDUSTRIAL LIVESTOCK PRODUCTION

The use of manure and slurries from livestock for AD shows the highest potential for emissions savings – mainly because of the staggering volumes produced by the intensive livestock sector. However, processing slurries may not be economically viable without huge subsidies, because slurries and manure have a very low energy density per tonne, which is why they are usually digested in combination with purpose-grown crops – which, as previously discussed, have questionable sustainability.

Again, there is a better alternative to AD – **preventing the manure and slurries from being produced in the first place (plus all the other emissions impacts of intensive livestock production), through reduced meat and dairy production and consumption.** This would reduce emissions substantially more than the mitigation potential offered by AD, and also has the potential to free up vast quantities of land for tree planting and additional carbon sequestration. The emissions mitigation from processing manure also significantly declines in future decarbonisation contexts because emissions from slurry storage and fertiliser production are projected to decline anyway.

A report commissioned by the Committee on Climate Change (CCC) estimates that a 50% reduction in the UK's beef, lamb and dairy consumption by 2050 could result in a 37% reduction in the total UK agricultural sector's domestic emissions by 2050 (CEH and Rothamsted Research, 2019, p. 29). It would also free up an estimated 4.2 to 6.9 million hectares of grassland[3]. If trees were planted on 4.2 million hectares, this would result in an estimated 54 million tonnes CO_2eq annual average carbon sequestration by 2032[4], which (assuming UK agriculture's emissions fall by 37%) would be enough to offset remaining UK domestic agricultural emissions nearly twice over[5]. Dietary shifts away from chicken and pork are also very effective – on average, switching from poultry meat to tofu results in reductions of 65% in emissions and 69% in land use (Poore and Nemecek, 2018 Figure 1).

AD subsidies may also actively facilitate the expansion of intensive livestock farming, through lowering the costs of waste disposal and helping factory farms obtain planning permission. The UK AD industry is advocating for AD subsidies to be raised to the same levels as in the early 2010s, which are roughly equivalent to the levels of AD subsidies which facilitated an explosion of intensive factory farming in Northern Ireland. **In this case, AD risks perpetuating and expanding the very polluting industry whose environmental effects it proposes to mitigate.**

3 The figure of 4.2 million hectares is 50% of the pastureland which Harwatt and Hayek (2019) estimate is currently used for animal agriculture. The higher figure is from the report commissioned by the CCC, which compares land use savings relative to a future 'business as usual' scenario where 12.26 million hectares of grassland are assumed to be used for agricultural production by 2050.

4 Extrapolated from Harwatt and Hayek (2019).

5 Based on the UK's domestic agricultural emissions in 2018: 45.4 million tonnes CO2eq (BEIS, 2020).

To make the best use of AD's potential for the mitigations emissions from manure production, we recommend that subsidies for AD of manure feedstocks should be reserved for smaller-scale, more sustainable livestock farms which have been in operation for at least 10 years and intend to own a stake in the AD plant. This support should be conditional on the farm not expanding its livestock production. Carbon, methane and ammonia emissions should be taxed (which would also disincentivise sending food waste to landfill), the 2027 ban on uncovered slurry and manure stores should be brought forward, and other measures should be taken to disincentivise the most environmentally destructive livestock farming. These measures will incentivise farmers to invest in AD over more damaging disposal methods, but will also make the most polluting sections of the livestock industry less financially viable. Revenues raised from these taxes could be used to fund a just transition for farmers into plant-based protein production, lower-impact meat production and becoming eco-stewards of newly afforested national parks. These schemes should be complemented with increased taxation on imported meats and animal feed, to ensure UK production is not simply replaced by imports.

Pig manure lagoon, Sussex.
Credit: Farms Not Factories

A ROLE FOR AD IN A SUSTAINABLE NET ZERO FUTURE?

Climate science tells us that only the highest ambition will save us from the climate crisis. Especially fast and deep cuts in emissions are required in rich countries if climate equity is to be achieved (Civil Society Review, 2018; Climate Equity Reference, 2019; Jackson, 2019), and current pathways to achieve net zero emissions by 2050 show no signs of bringing about such cuts. To avoid catastrophic global heating, we need to imagine the most ambitious path we can to a better future and throw everything we have at making this a reality, using the best available evidence as our guide. Where AD is not the optimal solution, we do not have the luxury of settling for second best.

AD does have a 'sustainable niche', but it is much smaller than the role the industry envisages for itself. As a destination for food waste that cannot be prevented or sent to animal feed, AD can be preferable to landfill. It also mitigates manure and slurry emissions where meat and dairy are produced within a sustainable food system, for example as part of a mixed, regenerative and nutritionally optimised agricultural system. While we should not let 'perfect be the enemy of the good', nor should we use public funds to prop up an industry whose primary goal is the optimisation of profits, not the true minimisation of emissions.

We hope this report kick-starts a much-needed conversation about AD's role in a rapidly decarbonising economy. It is time to broaden our imagination to encompass the possibilities if we stop wasting land and resources, and start using them instead to restore nature, tackle the climate crisis and ensure high quality, healthy and planet-friendly diets.

1. INTRODUCTION

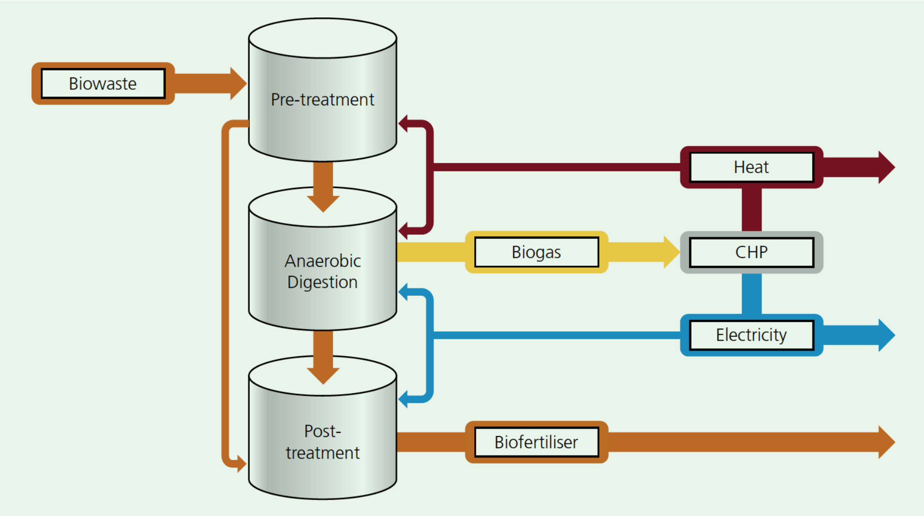
To achieve a circular, net zero GHG economy as soon as possible, it is urgently necessary to identify the sustainable niche for AD – where it provides the best environmental outcome, and where it is a suboptimal choice in competition with better alternative uses for feedstocks and land. Studies to date have mostly compared AD to alternatives with high environmental impacts (such as electricity production from oil) in present-day contexts, with which AD compares favourably. However, to keep climate change within a safe 1.5°C global temperature increase, rapid shifts are necessary in short time frames, especially with regard to energy and land use. There is currently a gap in research comparing AD to renewable energy such as wind and solar, and to more sustainable alternatives such as afforestation of land, dietary shifts to less meat consumption, and ensuring that wasted food instead goes to human (or animal) consumption where possible. This affects both the alternatives that AD is compared with, such as the GHG emissions of energy production (currently dominated by fossil fuels but shifting more to renewables), and the future availability of feedstocks for AD. This report is the first to shed light on the sustainable niche for AD in different future scenarios, including an ideal net zero GHG future.

In this report, we will first introduce AD, the industry and investors behind it, and their environmental promises and ambitions for growth. We will then explore the subsidies that have fuelled the growth of the industry to date, and explore the subsidy increases the industry wants to see next. We detail how the environmental benefits of AD have been overstated, exploring how sending different crops, food waste and manure to AD compares to better alternatives like preventing food waste, reduced consumption of meat and dairy, and using spared land and resources for food production, afforestation or solar PV. We also examine how subsidies for AD, coupled with a lack of policy support for better alternatives, have created perverse incentives which stand in the way of food waste prevention, and perpetuate or even grow the intensive livestock industry. We discuss how land spared by better alternatives to AD could be used more positively. Finally, in light of our findings, we review how policies could best be designed to ensure that AD remains within its sustainable niche, and that better alternatives are prioritised.

WHAT IS ANAEROBIC DIGESTION?

Anaerobic digestion (AD) is a natural process whereby plant and animal materials (biomass) are broken down by micro-organisms in the absence of air. Suitable biomass inputs for AD include crops, wood, manure and slurries, crop residues and food waste.

In modern AD plants, biomass is placed inside a sealed tank or digester. Naturally occurring micro-organisms then digest the biomass, releasing a methane-rich gas (biogas). This gas can be used to generate heat or electricity, or a combination of both though a combined heat and power (CHP) system (Alberici, Toop and Critchley, 2018, p. 27). The remaining material (biofertiliser/digestate) is rich in nutrients and can be used as a fertiliser.



Source: (Defra and DECC, 2011, p. 5)

Biogas is made up of about 50–70% methane and 25–50% carbon dioxide with traces of other gases, and is usually at least partially used on-site to help power the AD plant through CHP units (Alberici, Toop and Critchley, 2018, p. 27). Biogas can be used as an alternative to natural gas, but it has a lower caloric value and may cause corrosion and mechanical wear unless scrubbers are deployed, because it contains trace elements of hydrogen sulphide (Alberici, Toop and Critchley, 2018, p. 28)

Biogas can be upgraded to purer biomethane, which fetches a higher net price and can be injected into either the national gas grid or a local network (Alberici, Toop and Critchley, 2018, p. 28), allowing it to be sold to energy suppliers such as British Gas, E.ON and EDF Energy. The carbon dioxide which is removed during this process could be compressed and transported for sequestration, but the small scale and wide distribution of AD plants is likely to make carbon capture and storage (CCS) unviable (Alberici, Toop and Critchley, 2018, p. 28).

ENVIRONMENTAL PROMISES OF THE AD INDUSTRY

In 2019, the World Biogas Association (WBA) published its *Global Potential of Biogas* report, which claimed that AD has the potential to reduce global GHG emissions by 10–13% (World Biogas Association, 2019b, p. 1) – a projection which it presented at COP25 (Benson, 2019b). The first World Biogas Summit was jointly organised by ADBA and the WBA and hosted in Birmingham in July 2019[6] (ADBA, 2019e), illustrating both the UK's key role in championing AD worldwide, and the recent increase in global coordination in the AD industry to push for expansion. UNFCCC Secretariat (UN Climate Change) Manager Niclas Svenningsen, speaking at the World Biogas Summit, said that AD "needs to be at the table when the future policies of governments are designed, when NDCs are reviewed and taken to the next level" (ADBA, 2019c). The ADBA says that the upcoming COP26, hosted in the UK, is a "unique opportunity to put the UK biogas industry on the map" and to "assert its potential to contribute to the UK's Nationally Determined Contribution" (ADBA, 2019c).

6 This took place alongside the UK AD & World Biogas Expo 2019, the largest international trade show dedicated to AD and biogas: https://www.thenec.co.uk/whats-on/world-biogas-summit/

Source: (ADBA, 2019a)

Domestically, ADBA claims that the AD and biogas sector is currently cutting UK emissions by 1% annually, with the potential to reduce annual emissions by 6% (ADBA, 2020a). This is based on ambitious projections of growth – that "all organic wastes readily available in 2030 are collected and digested" (170 million tonnes, compared with about 30 million today), and 4.2 million tonnes of energy crops grown over 282,900 hectares are digested to generate enough biomethane to heat 5.5 million homes (ADBA, 2020a)[7]. ADBA Chief Executive Charlotte Morton says that "I don't believe that the UK can achieve its Net Zero targets without it" and that it is particularly important for "hard-to-decarbonise sectors such as agriculture, transport and heating" (Benson, 2019a). In 2019, ADBA's national conference was called *There's No Net Zero Without Biogas* (ADBA, 2019b). Beyond this, the AD industry pitches itself as key to the circular economy, emphasising its own circular use of organic wastes (ADBA, 2020a, p. 5).

WHAT ARE THE PRODUCTS OF AD?

ELECTRICITY

The WBA estimates that AD could provide 16–22% of the electricity consumed globally, if all future AD capacity was used to generate electricity (World Biogas Association, 2019b, p. 2). In the UK, the AD industry estimates that, at its full potential, AD could provide 21% of total UK electricity demand if all AD was used to generate electricity (ADBA, 2020a, p. 1).

Total emissions from AD are usually compared with the current energy mix in a given country, or against fossil fuels – with which AD compares favourably (Meyer-Aurich *et al.*, 2012; Timonen *et al.*, 2019). However, AD has rarely been compared with more sustainable alternatives like wind and solar, which need to rapidly become a more prevalent part of our energy mix to avoid climate crisis.

So how does AD compare with other renewables? One benefit of AD is that it can generate power almost all of the time, consistently – whereas power from other renewables like solar and wind is often intermittent, dependent on the weather. However, a comprehensive study comparing electricity generated from biogas produced by AD with other renewable energy sources found that when any feedstock other than manure was used, "biogas systems generate higher greenhouse emissions than any of the renewable options" including wind, solar PV and hydro (Fusi *et al.*, 2016).

There are some questions over the land use efficiency of using AD of crops to produce electricity. For instance, Germany used 7% of its arable land to grow biogas substrate (mainly maize) in 2011, but this only generated 3% of Germany's national electricity consumption (Herrmann, 2013, p. 382) – a large area of agricultural land to sacrifice for a low return, with risks of displacing or offshoring food production, and indirect land use change.

7 The extra waste feedstocks are assumed to generate an extra 35.8TWh of biogas production (ADBA, 2020a).

In terms of cost too, wind and solar significantly outperform biogas plants – with electricity from biogas plants offering generation costs of 10–15 cents/kWh, compared to 4–8 cents/kWh for electricity from onshore wind and huge solar systems (Bahrs and Angenendt, 2019)[8]. However, the AD industry is keen to point to the results of an Italian study which found that the "cost structure of biomethane may be competitive with solar and wind renewables when considering the intermittent nature of solar and wind" (ADBA, 2018, p. 10).

The CCC recently concluded that large-scale AD plants producing electricity **"have potentially limited roles in contributing to achieving net-zero emissions by 2050** if they cannot be subsequently fitted with CCS" so should be deprioritised for electricity subsidies, recommending that where AD is used, biomethane production is prioritised (Committee on Climate Change, 2020b). As we demonstrate later in this report, even assuming CCS is fitted, many AD feedstocks provide only minor emissions savings in future decarbonisation contexts. As a result, the AD industry itself says that its main focus for growth is biomethane production for heating and transport. However, despite this, it still advocates for higher electricity subsidies for AD and argues that AD has a role in producing electricity during periods of peak demand or when solar and wind might be less active (ADBA, 2020a, pp. 10–11). 80% of current AD plants in the UK generate electricity (ADBA, 2020a, p. 19).

Credit: Ssuaphotos

BIOGAS AND BIOMETHANE

One of the biggest selling points for AD is that it can also be used to produce biogas. The WBA claims that AD could replace 26–37% of the natural gas currently consumed, if all future AD capacity was used to produce biomethane (World Biogas Association, 2019b, p. 2). In the UK, the AD industry projects that 8 billion m^3 of biomethane could be produced through AD – enough to displace "22% of current fossil gas demand for domestic heat" or "70% of the UK's bus and heavy goods vehicle (HGV) energy demand" (ADBA, 2020a, p. 1).

One of the products of the AD process is methane, which can then be burned for energy, releasing the less potent GHG carbon dioxide. The WBA claims that "Methane has a global warming potential 28 times higher than CO_2 and therefore its capture and use can reduce total emissions by 25 to 40 times the level of an equivalent capacity of solar or wind power" (World Biogas Association, 2019a). It is unclear what "equivalent capacity" this could possibly refer to, since the evidence is fairly clear that, per kWh produced, solar and wind power result in substantially higher emissions savings than AD (Fusi *et al.*, 2016).

Waste-to-energy technologies are seen as particularly useful for generating renewable heat for systems that are difficult to electrify, and as a potential (more sustainable) fuel for heavy transport and shipping, which are more difficult to electrify than passenger cars (DAC Beachcroft, 2019). Hence, biomethane, for export to the gas grid and as fuel for transport, is the main focus of the AD industry's future expansion plans (ADBA, 2020a).

8 Euro cents

However, there is a risk of "natural gas lock-in" if we treat natural gas as a "bridge fuel" to a sustainable energy mix, and thus end up locked into long-term gas infrastructure investments (Fitzgerald, Braunger and Brauers, 2019). **This gas infrastructure, alongside AD infrastructure, may also risk locking in biogas as a preferable, but suboptimal, alternative.**

In the CCC net zero scenario for 2050, "a small amount of biogas (14 TWh) is assumed to be available after reductions in food waste, of which half is assumed to be used in gas-fired CCS power generation and the other half is used to displace natural gas in industry (79%) and buildings (21%)" (Committee on Climate Change, 2019c, p. 149). It is notable that this projection is far lower than ADBA's projection of 80 TWh annually by 2030 (ADBA, 2018, p. 15), raising questions about whether it is prudent to lock in AD infrastructure – particularly if the UK decides to aim for net zero significantly before 2050 (as it must for us to keep average temperature increases due to climate change within safe levels).

DIGESTATE

One of the key outputs from AD is digestate – a nutrient-rich substance which can be used as a fertiliser. The volume of digestate is approximately 90–95% of the material originally fed into the digester (Biogas Info, 2019).

The WBA claims that, in the future, digestate produced through AD could replace 5–7% of inorganic fertiliser currently in use, and "fertilise 82 million hectares of land, equivalent to the combined arable land in Brazil and Indonesia" (World Biogas Association, 2019b, p. 2). In the UK, the CCC also suggests that greater efficiency in nitrogen use could be achieved through measures including "more use of organic residues (e.g. anaerobic digestates)" (Committee on Climate Change, 2018, p. 38).

One of the greatest environmental benefits of AD is that, by acting as a replacement for synthetic fertilisers, it can displace the environmental impacts of their production (Styles *et al.*, 2015; Timonen *et al.*, 2019), which involves very high pressure and temperatures (Farm Carbon Toolkit, 2019). However, most of the GHG emissions associated with fertilisers come from the soils to which they are applied. Digestate is a good fertiliser because it has high nutrient content in available form, meaning it is a good candidate to replace inorganic fertilisers and to contribute to short-term organic matter turnover (Tambone *et al.*, 2010).

BOX 1 – HOW IS DIGESTATE DIFFERENT FROM COMPOST?

Compost and digestate have similar, but distinct, qualities – with digestate closer in properties to synthetic fertilisers. The key differences (which should be taken as general trends) can be seen in Table 1 below:

Table 1: Comparison between digestate, compost and synthetic fertilisers:

Property	Compost	Digestate	Synthetic fertiliser	Source
Type of micro-organism digestion	Aerobic (with oxygen)	Anaerobic (without oxygen)	N/A	(Biogas Info, 2019)
By-product	Carbon dioxide	Methane	Various	(Biogas Info, 2019)
Increases yields with no negative impacts on crop quality or safety	Yes	Yes	Yes	(WRAP, 2016a)
Readily available nitrogen content (boost to short-term crop yields)	Lower	Higher	Higher	(WRAP, 2016b, p. 11) (WRAP, 2015, p. 10 Table 5)
Effectiveness at building up long-term organic soil nitrogen reserves (and long-term soil fertility)	Higher	Lower	Lower	(WRAP, 2016b, p. 11)
Risk of atmospheric emissions (i.e. ammonia, nitrous oxide, methane) and leaching losses (nitrate, soluble phosphate and E. coli)	Lower	Higher	Higher	(WRAP, 2016b, p. 11)
Nitrogen in mineral form (see 'Environmental impacts' section below for information about why this matters)	No	Yes	Yes	(Poux and Aubert, 2018, p. 24)

It should be noted that the average level and type of nutrients contained in digestate varies depending on whether the digestate was made by processing food waste, crops or manure (WRAP, 2016c, p. 9), so the information in Table 1 is only a general guide. After manure is treated by AD, the resulting digestate has more 'bioavailable' nutrients than the original raw slurry, so it is easier for plants to make use of the nutrients – this is useful, as the material is often spread on land without further processing (ADBA, 2012).

ENVIRONMENTAL IMPACTS

The AD industry claims that digestate will "regenerate our depleted soil" (ADBA, 2020a, p. 18). However, digestate and synthetic fertilisers present similar problems, such as lower effectiveness in building up long-term soil fertility, higher nitrate emissions and leaching into waterways (WRAP, 2016b, p. 11). Consequently, it would seem that digestate maintains most of the issues that synthetic fertilisers pose for our soils. Moreover, digestate from AD contains mineral nitrogen, and high levels of mineral nitrogen foster the development of fungal diseases and weeds in plots, leading to higher herbicide use. For these reasons, the authors of a recent paper concluded that AD should have no role in an agro-ecological farming system (Poux and Aubert, 2018, p. 24). The readily available nitrogen in digestate is mostly in the form of ammonium, which can result in high economic and environmental costs if mismanaged (WRAP, 2016b, p. 10). As noted in Table 1, the risk of atmospheric emissions and nitrates leaching through the soil into nearby waterways is higher for digestate than for compost, so it must be ensured that digestate is not dumped in high concentrations on land at risk of being overloaded with nitrates. Currently, 62% of land in England and 4% in Wales is classified as nitrate vulnerable zones (NVZs), which are areas designated as being at risk from agricultural nitrate pollution. Thus, digester operators need to consider whether there is enough land close to the digester that can accept the digestate within the restrictions of NVZs (Biogas Info, 2019)[9]. Where there are limited outlets to sell digestate and large volumes to dispose of, there may be temptations to land spread it irresponsibly. Most digestate produced currently is liquid. By the AD industry's own admission, this is "inconvenient to transport and harder to store" and comes with risks of ammonia emissions, limiting its market value. However, while converting it to "dried" digestate solves some of these problems, the dried form "requires a lot of energy to produce", potentially compromising its sustainability (ADBA, 2020a, p. 24).

Negative effects can be minimised through best practices, such as only applying digestate where crops require nitrogen (and so will absorb the nitrates), or using precision application methods like band spreading or shallow injection (WRAP, 2016b, p. 10)[10]. Applying digestate in the spring also results in significantly higher nitrogen use efficiency for food and manure-based digestates compared with autumn application, as a result of high levels of nitrate leaching over winter (WRAP, 2016b, p. 5).

---

9 This can be done through the AD calculator: https://www.nnfcc.co.uk/publications/tool-ad-cost-calculator

10 Band spreading is the placement of fertiliser in a concentrated layer or location (band) in the soil, commonly 8–15 cm below the surface. Shallow injection is the application of liquid manure by placement in shallow, vertical slots, typically about 50 mm deep and 25–30 cm apart, cut into the soil by a tine or disc. Source: (Eurostat, 2020)

2. THE ANAEROBIC DIGESTION INDUSTRY

Credit: Riko Best

CURRENT INDUSTRY STRUCTURE

The WBA estimates that there are 50 million micro-digesters, 132,000 small-, medium- and large-scale digesters, and 700 upgrading plants operating globally (World Biogas Association, 2019b, p. 1). In 2019, these digesters had an estimated capacity of 60 MW (Visiongain, 2019).

The AD industry is supported by various incentive schemes across Europe to cultivate its growth, such as feed-in tariffs (FiTs) (Kampman *et al.*, 2016, p. 39). Germany was the earliest adopter of AD at scale in the EU and has the largest capacity (mainly using maize feedstocks) in Europe, followed by Italy and the UK (Kampman *et al.*, 2016, p. 58).

In September 2011, only 68 AD plants were operational in the UK, rising to 140 by September 2014, which nearly quadrupled the installed capacity of electricity generation from AD (Defra, 2015, p. 3). During the early-mid 2010s, the industry remained highly fragmented, with no operator owning more than five operational facilities in 2015 (Moore, 2013). By April 2019, there were 486 operational AD plants in the UK[11], including 84 biomethane-to-grid plants, with a further 343 AD projects under development (NNFCC, 2019)[12]. Greater industry consolidation has occurred as the industry has matured, though there is still a wide range of sizes and types of AD plants (DAC Beachcroft, 2019).

UK AD plants collectively generated 2.7 TWh in 2018, with a capacity of 0.5 GW as a result of 26 new sites coming online (BEIS, 2019b, p. 118) – compared with the UK's 450 TWh of natural gas production and 300 TWh of consumption of electricity in 2018 (BEIS, 2019a). AD energy generation grew by 30% between 2017 and 2018, mainly as a result of greater RHI-subsidised exports of biogas to the grid (BEIS, 2019b, p. 120).

11 This does not include water treatment facilities or those treating sewage sludge.

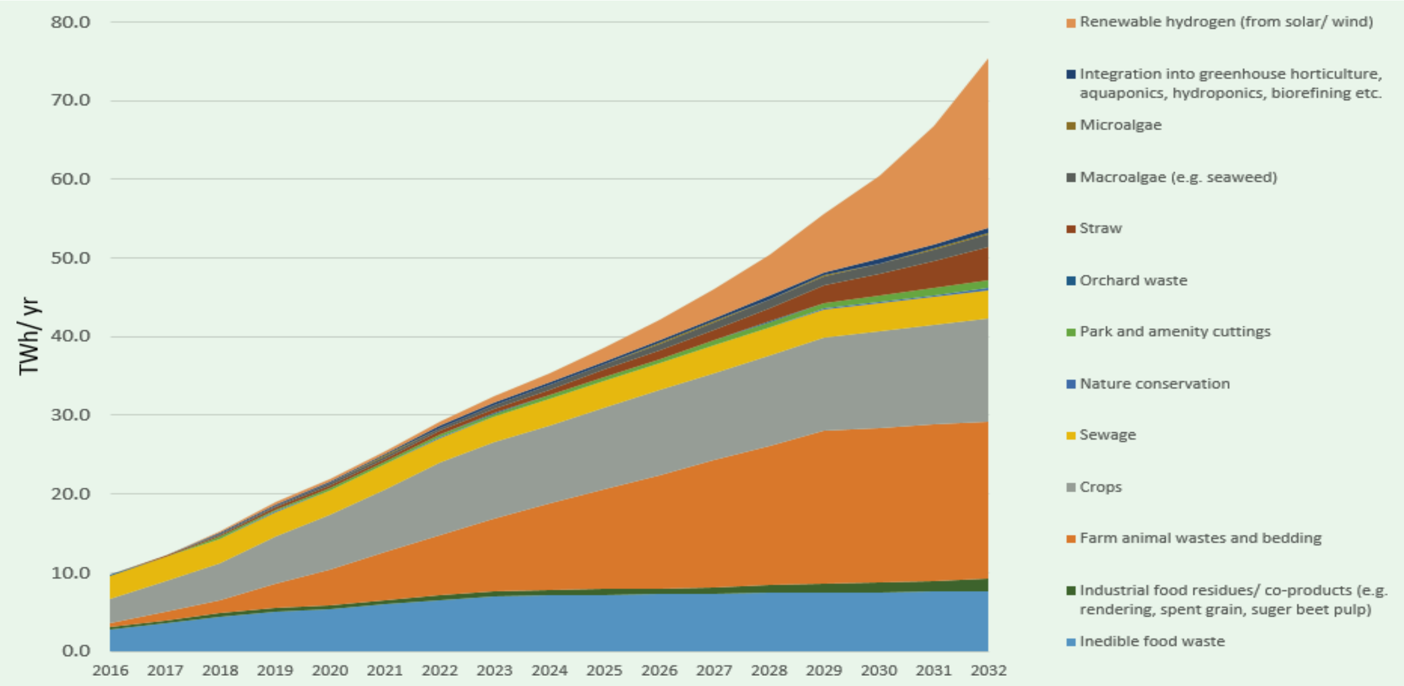
12 ADBA estimates a higher number of AD plants. See http://adbioresources.org/adba-market-policy-reports

AMBITIONS FOR GROWTH

The industry plans significant growth. The WBA claims that globally "we are tapping into just 1.6–2.2% of the global potential of AD" and potential growth is "extraordinary" (World Biogas Association, 2019b, p. 1). Globally, AD is projected to reach $31.5 billion in capital expenditure and 44 GW in capacity by 2029 (Visiongain, 2019).

ADBA projects that "with the right government support", the UK's AD industry has the potential to generate 80 TWh annually by 2030, enough to deliver around 30% of domestic electricity or gas demand, or to power nearly every HGV in the UK (ADBA, 2018, p. 15). From the baseline of 2.7 TWh generated by AD in 2018 (BEIS, 2019b, p. 118), this would mean the industry growing to around 30 times its current size[13]. ADBA claims that the AD industry "has the potential to employ 35,000" people, 10 times the current level, by 2030 (ADBA, 2018, p. 12). If the UK government adopted its recommended policies, ADBA anticipates 100 new AD plants being built every year (WRAP, 2019a). ADBA also projects that nearly half of energy 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 (ADBA, 2018, p. 16)[14] – see figure 1 below:

Figure 1: Biomethane 'high' potential from AD and renewable hydrogen TWh/year



Source: (ADBA, 2018, p. 16)

13 Even if we assume that the load factor of AD was increased from its current average of 62.7% (BEIS, 2019b, p. 118) to 100% (i.e. the plants generated energy all of the time, 24/7), then the industry would still need to expand to a minimum of 16 times its current size to generate 80 TWh.

14 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 recent literature questioning the sustainability of using crops for AD.

3. SUBSIDIES AND SURVIVAL

ECONOMICALLY VIABLE?

AD is currently highly reliant on subsidies for survival. For instance, solar and wind power are significantly cheaper means of producing electricity than AD, such that "many more innovations are needed throughout the biogas value chain for it to be competitive in energy markets without high subsidies" (Bahrs and Angenendt, 2019, p. 9). ADBA stresses that, currently, AD plants of any size "cannot be run profitably solely through wholesale [electricity and gas] prices" (ADBA, 2020a, p. 31), so they require subsidies and other revenue streams. It openly states that "the financials do not currently stack up for new biomethane projects without support from the government" (ADBA, 2020a, p. 48). However, biogas may attract higher demand as a more sustainable alternative to natural gas.

As well as selling biogas, electricity or biomethane, the AD industry also sells digestate. However, ADBA claimed in 2018 that "digestate currently has a low or even negative commercial value and one of the goals of the 2018 bioenergy strategy should be to continue to improve its quality, availability and its value" (ADBA, 2018, p. 2).

The AD industry also earns revenue from "gate fees" (or "tipping fees") paid by local authorities and industry for the disposal and treatment of food waste, and sometimes other waste (Dick and Scholes, 2019b, 2019a). When feedstocks are scarce or demand is very high, AD operators pay for waste rather than charging for its collection. For more information on AD gate fees, see Appendix 1.

PREVIOUS SUBSIDY SYSTEMS

Generous subsidy schemes such as the FiT and the Renewables Obligation (RO) were provided to AD in the early 2010s. These were then gradually reduced and eventually mostly replaced with new subsidy mechanisms. While these early schemes are now closed to new applicants, they are still significant for the AD industry, because most of them are paid for up to 20 years from the point (and at the rate) originally agreed. This means that AD plants built in the early 2010s are often still paid a higher level of subsidies than AD plants built later. For instance, we estimate that a 1 MW AD plant built in 2012, producing biogas and operating 73% of the time, would still have received around £700,000 annually in FiT subsidies in 2018/19, accruing about **£14 million over 20 years** until 2032. Many AD plants will still be operational and claiming these subsidies for many years to come. The RHI for biogas and biomethane was also significant, and is still operational, albeit at a reduced rate. The AD industry has strongly objected to any reduction in these subsidies – for instance, when FiT subsidies were reduced between 2014 and 2018, ADBA complained that the "Feed-in Tariff is capped to just 5MW per quarter and the tariff is too low to attract new applicants" (ADBA, 2018, p. 10). For more information on past subsidies, see Appendix 2.

CURRENT SUBSIDIES

A very simplified overview of the subsidies currently available to newly built AD plants is provided in Table 2 below, to give a general illustration of subsidy levels[15]. The actual subsidies are more complex – for a more detailed and nuanced explanation, see Appendix 2.

Table 2: Subsidies and incentives currently available to newly built AD plants

Energy type	Subsidy scheme	Subsidy level	Estimated subsidy per year	Details
Heat (biogas)	Renewable Heat Incentive (RHI)	**1.18–4.74 pence per kWh** depending on plant size, with lowest subsidy rate for plants bigger than 600 kWth	**£380,394** for 4 MW AD plant **£95,100** for 1 MW AD plant[16] **£149,901** for 0.5 MW AD plant **£57,301** for 0.15 MW AD plant (Calculated by Feedback)	The most significant subsidies currently available to AD plants are RHI tariffs, which have been in place since 2009. RHI subsidies for biomethane from AD were introduced around 2013/14. Once granted to an AD plant, RHI subsidies are paid for 20 years at the original agreed rate. There was a marked decrease in RHI tariffs between 2016 and 2018, with industry players claiming rates did not keep up with construction costs for AD plants (DAC Beachcroft, 2019). RHI tariffs were increased once more in mid-2018, though not to levels as high as pre-2016. At current rates, a I MW AD plant would receive **£1.9 million for biogas or £7.6 million for biomethane over 20 years**. ADBA predicts that the 2018 increase in subsidies will trigger £150–300 million in investment and the development of more than 50 gas-to-grid plants (DAC Beachcroft, 2019). Since 2011, RHI has been the most important force in driving biomethane-to-grid AD plants, supporting the development of 108 plants by 2020 (ADBA, 2020a, p. 34). RHI subsidies currently favour larger AD plants, with the combined revenue of wholesale gas plus subsidies via RHI only exceeding construction and operational costs at plants bigger than 0.5 MW (ADBA, 2020a, p. 35).
Heat (biomethane)	Renewable Heat Incentive (RHI)	**4.86 pence per kWh** for first 40,000 MWh **2.86 pence per kWh** for next 40,000 MWh **2.21 pence per kWh** thereafter (2019/20)	**£1.57 million** for 4 MW AD plant **£382,000** for 1 MW AD plant **£98,000** for 0.25 MW AD plant (Calculated at top rate of 4.86 pence, would decline in subsequent years) Source: (ADBA, 2020a, p. 34)	
Electricity (small-scale, up to 5MW)	Smart Export Guarantee (SEG)	Varies by energy provider: **1.5 pence per kWh** (British Gas, 2020) **4 pence per kWh** (Scottish Power, 2020) **5.38 pence per kWh** (Bulb, 2020)	For 1 MW AD plant: **£120,888** (British Gas) **£322,368** (Scottish Power) **£433,585** (Bulb) (Calculated by Feedback)	Launched in January 2020, effectively replacing FiTs, which closed to new applicants from 1st April 2019, the SEG obliges licensed electricity suppliers (like British Gas) to offer a tariff to small-scale low-carbon generators exporting electricity to the National Grid, but allows those licensed electricity suppliers to set their own rates for the tariff they offer (Ingrams, 2019). In most cases, payments provided under the SEG are less generous than FiTs, where a fixed subsidy price was set by Ofgem and the government (Ingrams, 2019). Companies agreed tariffs of between 0.5 and 5.5 pence per kWh for eligible technologies in January 2020. At these rates, ADBA says that AD plants will make a loss, and the rates would need to be at around 4.8–8 pence/kWh even for new plants operating at 92% capacity to make a profit (ADBA, 2020a, p. 33).

15 Figures in this table assume AD plants operating at 92% capacity, in line with ADBA's most optimistic assumptions of the operating capacity of new AD plants – although the average operating capacity is currently 70–75% (ADBA, 2020a). AD plants operating at lower capacity would claim slightly lower levels of subsidy.

16 1 MW plant has a lower subsidy level than the 0.5 MW plant because larger AD plants are subsidises at such a lower rate per kWth.

Energy type	Subsidy scheme	Subsidy level	Estimated subsidy per year	Details
Electricity (large-scale, over 5 MW)	Contracts for Difference (CfD)	Topped up to **13.5–15 pence per kWh** (2012 prices) if market price falls below this level; if electricity price exceeds this rate, recipients pay back excess	Depends on the market price	CfD started in 2014 to replace the RO, which eventually closed in March 2017. So far, three CfD allocation rounds have occurred, with rounds 2 and 3 only open to "less established technologies", which includes AD projects over 5 MW in capacity (Department of Energy and Climate Change, 2014), but has to date controversially excluded onshore wind as a result of a 2015 Conservative manifesto promise (Smith, 2019). However, the Conservative government has recently signalled a revival in support for onshore wind (Ambrose, 2020). Future rounds are expected every two years, and will probably also focus on "less established technologies" including AD (BEIS, 2017). ADBA has been highly critical of CfD, claiming that only funding AD plants with over 5 MW capacity excludes the "vast majority of plants" (Nierynck, 2016).
Fuel (biomethane)	Renewable Transport Fuel Obligation (RTFO)	**57–76 pence per kg of biomethane** from wastes and residues **28.5–39 pence per kg of biomethane** from energy crops (approximately, as the rates fluctuate)	**£1.58 million** for 4 MW AD plant **£385,000** for 1 MW AD plant **£99,000** for 0.25 MW AD plant (assuming average 17.9 pence per kWh RTFC price from 2019 and 100% waste-based feedstock – if the feedstock contains a significant portion of bioenergy crops, annual revenue is roughly halved) Source: (ADBA, 2020a, p. 34)	Very few AD plants currently supply biomethane for transport, but this is likely to become more important in future. The government issues renewable transport fuel certificates (RTFCs) to fuel suppliers, who then use these to demonstrate that they are meeting their obligations to provide a percentage of their fuels from renewable sources (Department for Transport, 2020). These certificates can be traded, or sold on to companies that need them to comply with RTFO (Department for Transport, 2020). Biomethane producers can currently claim both RHI and RTFC payments within the same year, but for each quarter of the year must pick one to claim (ADBA, 2020a, p. 34). RTFO subsidies currently favour larger AD plants, with the combined revenue of wholesale gas plus subsidies via RTFO only exceeding construction and operational costs at plants bigger than 0.5 MW (ADBA, 2020a, p. 35).
Heat or fuel (biomethane)	Biomethane certificates	**£2 per certificate** (average price pre-2019) **£9 per certificate** (average 2019 price)	**£64,000–290,000** for 4 MW AD plant **£16,000–73,000** for 1 MW AD plant **£4,000–18,000** for 0.25 MW AD plant (Based on £2–9 per certificate) Source: (ADBA, 2020a, p. 34)	Biomethane's green credentials may be sold on the private market through biomethane or green gas certificates, which operate in a similar way to RTFCs. An AD plant may sell biomethane certificates on top of claiming subsidies through either RHI or RTFC for a given annual quarter (ADBA, 2020a, p. 36). Certificate prices are purely market-driven, and their price post-2019 is expected to increase (ADBA, 2020a, p. 36). A 1 MW AD plant selling certificates over 20 years at the higher £9 per certificate price could earn **£1.5 million over 20 years** (ADBA, 2020a, p. 36).

FUTURE SUBSIDIES

With current support for AD ending by the close of 2021, the battle is on to determine the future subsidies regime, and the AD industry is currently lobbying hard for support to be extended (Davidson, 2019). Industry representatives argue that it deserves subsidies to help it find its feet, with ADBA Chief Executive Charlotte Morton saying that "Other renewable industries, such as wind and solar, have enjoyed consistent support and are now extremely cost-effective and established as part of our renewable energy mix. AD and biogas should be given the same fair treatment now so that it can realise its huge potential towards decarbonising the UK economy by 2030" (Davidson, 2019).

The AD industry is hungry for higher subsidies. ADBA claims that "incentives closer to the 2013–15 rates are initially required" (ADBA, 2020a, p. 48), because during this period over 100 new AD plants were built per year. For the AD industry to reach its full potential, ADBA says growth must be even faster than this (ADBA, 2020a, p. iii). In practice, RHI and FiT subsidy rates during this period were in the range of 7.9–17.5 pence per kWh – significantly higher than current rates (ADBA, 2020a, p. 48). Since 2018, as AD subsidies have declined, fewer than 20 new AD plants have opened each year (ADBA, 2020a, p. 48). The prospect of raising subsidies to 2013–15 levels is highly concerning. For instance, there is a risk that setting subsidies this high will divert food down the food waste hierarchy, divert land from food production and afforestation to bioenergy crops, and incentivise the perpetuation or even expansion of intensive livestock farming (see sections 5-7 below).

The AD industry also ideally wants a return to tariffs guaranteed by the state, rather than (or as a supplement to) market-based support such as the SEG where the price paid fluctuates more and there is often no guaranteed minimum price. ADBA argues that uncertainty reduces investor confidence and increases the costs of finance (ADBA, 2020a, p. v). Where the support given is market-based, the industry wants the state to institute a minimum price to be paid by the energy sector (ADBA, 2020a, p. 44). ADBA has also been enthusiastic about RHI being extended (or replaced by another scheme) for new AD plants exporting biogas or biomethane (ADBA, 2018). The AD industry is also calling for RTFO to be extended beyond 2032, and for a price guarantee to be set (ADBA, 2020a, p. iii).

In addition, there seems to be implicit support within the industry for the system of 20-year-long guarantees for subsidies which characterised previous systems like RHI. The industry explicitly calls for the government to guarantee higher subsidy rates long into the future so that investors can have "certainty regarding AD's long-term future", opposing the system of funding being announced and allocated every few years (ADBA, 2020a, p. 49).

Whereas most subsidies are currently tiered, with larger subsidies given to smaller AD facilities, the AD industry wants a flat (or flatter) rate so that larger AD plants can claim the higher subsidy rate too, on the basis that larger plants provide economies of scale and thus provide better value for money for the state per unit of energy produced (ADBA, 2020a, p. 50).

Despite its claims that AD should be targeted at biomethane production for hard-to-decarbonise sectors, ADBA also protests that subsidies for electricity produced by AD are too low to incentivise growth (ADBA, 2020a, p. 48). When FiT ended for all new small-scale AD plants exporting electricity to the grid in April 2019, the AD industry called on the UK government to "introduce a bespoke low-carbon CfD scheme to support small-scale renewable technologies" (ADBA, 2019d), presumably in addition to SEG payments because these vary widely by energy company and are often set fairly low.

ADBA also calls for "lower business rates for the AD industry" (ADBA, 2020a, p. 45) and suggests tax breaks for various AD-related businesses including smaller AD plants processing manure and green waste, and businesses separating their food waste for collection by AD plants (ADBA, 2020a, pp. 50–52). On top of all this, they suggest government funding for a digestate certification scheme, research and innovations grants, and many other aspects of the AD industry (ADBA, 2020a).

More AD subsidies do appear to be on the way, but the scale of future subsidies for AD seems highly uncertain. In its 2018 Resources and Waste Strategy, the UK government laid out its plans to "carry out and publish a review of policies to support bio-waste recycling through anaerobic digestion and composting" (HM Government, 2018, p. 72). It "committed to spending £3bn by 2042 on developing new waste infrastructure", which is intended to help "give the private sector the confidence to invest in waste management projects" including "Anaerobic Digestion plants" (HM Government, 2018, p. 78). ADBA welcomed this, and said in 2019 that it had had "very encouraging" meetings with the Department for Business, Energy & Industrial Strategy (BEIS) (ADBA, 2019c). In January 2020, Boris Johnson confirmed that the government is looking into creating a successor to RHI, which ADBA welcomed (ADBA, 2020b).

In light of the findings of this report, we recommend that the scale and form of subsidies to AD need to be carefully designed to ensure that money and resources are not diverted from more environmental alternatives, and that subsidies do not have the perverse outcome of stimulating the AD industry beyond its optimal size.

WHO PROFITS FROM AD SUBSIDIES?

Investment in AD comes from a diverse range of sources – from farmers investing in small-scale AD to large-scale investors funding and buying up AD plants. However, because the upfront financial costs of setting up an AD plant are high, Big Finance is rarely far away. **Ownership of the AD industry is increasingly being concentrated and consolidated under the control of large investment companies**. For example, Bio Capital was formed as a collaboration between multiple investment funds in 2018 with the main aim of capitalising on the growth and consolidation of the AD industry by buying up AD plants (Private Equity Wire, 2018). These **investment companies often pay out large dividends to shareholders**. For instance, through its acquisition of Biogen, Ancala Partners LLP now owns 13 AD sites around the UK (Biogen, 2019). The company's net profits, generated for distribution to members for the 2018/19 financial year, were £5.49 million (Ancala Partners LLP, 2019, p. 2). This raises the **risk that shareholder returns may be prioritised over sustainability**.

Credit: Netfalls Remy Musser

ADBA maintains that investors require high profit rates of about 15% over a 20-year period to see AD as an attractive investment, and achieving this would require subsidy rates similar to those available in 2011–15: "investors must be confident that incentives are sufficiently high and for a long enough term" (ADBA, 2020a, p. 35). **In this way, considerable volumes of public money may be transferred to wealthy investment funds. This creates the driving force for the AD industry pushing for subsidies to be locked in at higher rates for decades into the future** – a pivotal time during which radical decarbonisation will be necessary and the sustainability of AD is likely to decline compared with better alternatives.

Since AD plants are often subsidised with considerable amounts of public money, it is also i**mportant to scrutinise whether there is a risk that the profits from AD plants are going to companies who do not pay a fair share of tax**. The major investors in UK AD plants are usually based in London's financial centre, but also sometimes in tax havens further afield, such as British overseas territories and Crown dependencies (see case study 1 below). In the Tax Justice Network's 2019 *Corporate Tax Haven Index*, Jersey ranks as the 7th worst facilitator of tax evasion globally, the UK ranks 13th (mainly due to London's role as an international financial centre) and Guernsey ranks 15th (Tax Justice Network, 2019). Whether companies engaging in tax avoidance or evasion while paying out large dividends to shareholders should qualify for public subsidies remains a matter of public debate[17].

17 There has quite rightly been a public conversation about whether companies like Virgin, which receive considerable public money for contracted services like railways and healthcare, should be given public money when they are based in tax havens and paying negligible UK tax.

CASE STUDY 1: FORESIGHT GROUP

One of the most prominent investors in anaerobic digesters is a labyrinthine network of companies with close links to tax havens. **Foresight Group LLP**, registered at The Shard in London, has £6.5 billion of assets under management (Foresight Group, 2020). It is a subsidiary undertaking of **Foresight Group CI Limited**, a private company registered in Guernsey, a noted tax haven with strong links to London's financial sector. Foresight has twice been the winner of the *Investment Week* 'Tax Efficiency Awards (Foresight Group, 2016, 2019). Despite being based in a tax haven, the group specialises in low-risk, long-term infrastructure projects which are underwritten with public money, including PFI contracts for institutions like schools and hospitals, as well as renewable energy like AD, promising reliable returns. For instance, one of its largest investment companies is **GCP [Gravis Capital Partners] Infrastructure Investments Ltd**, which financed the construction and operation of 11 AD plants via investments through **BCP Biomass 1 Ltd** into **Assured Energy LLP** (Assured Energy LLP, 2018, p. 5)[18]. Assured Energy owns and runs many of the anaerobic digesters in Northern Ireland[19]. Allegations have been made that Assured Energy approached a farmer, Raymond Pollock, with a proposal to finance and build a 500 kW AD plant on his land which would earn £800,000 a year in subsidies. However, once the plant was built, a dispute arose (including over environmental hazards), which Raymond Pollock says left him locked out of the operation (Macauley, 2018; SourceMaterial, 2018). GCP Infrastructure Investments Ltd is itself incorporated in another noted tax haven, Jersey, and its shares are traded on the main market of the London Stock Exchange (GCP Infrastructure Investments Limited, 2015, p. 1). The board of directors of GCP Infrastructure Investments Limited includes a non-executive director of Jersey Finance Limited, the promotional body for the finance sector in Jersey[20], and someone who previously worked for the Jersey Financial Services Commission – the current regulator of GCP Infrastructure Investments Ltd (GCP Infrastructure Investments Limited, 2019, pp. 48–49).

18 Foresight Group also owns other UK AD plants through John Laing Environmental (JLEN) Asset Group (Foresight Group, 2018; JLEN, 2019) and the Foresight Anaerobic Digestion (AD) EIS Fund, which primarily invests in on-farm AD projects (Foresight Group, 2019).

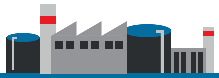
19 Assured Energy LLP is registered at Gravis Capital Management Ltd's offices in Savile Row, London.

20 As an example of the kind of work that Jersey Finance Limited does, in 2018, it was discovered that it secretly financed an Institute of Economic Affairs (IEA) report which attacked the idea that offshore financial centres were "hotbeds of tax evasion" (Booth and Pegg, 2018).

4. MODELLING THE 'SUSTAINABLE NICHE' FOR AD

To discover the potential role for AD in a sustainable future, Feedback conducted a consequential LCA in collaboration with experts at Bangor University (Styles *et al.*, 2020).

The study examined two scenarios[21], each modelled in three different decarbonisation contexts:



INDUSTRY-DRIVEN AD SCENARIO

The volume of feedstocks sent to AD is maximized, modelled based on a combination of the UK AD industry's ambitions for growth by 2030 and analysis of available feedstocks.

Hence, a significant volume of crops is sent to AD, and almost all available manure and slurries.

Food waste is assumed to be reduced in line with WRAP's current voluntary commitments for 2030, but all remaining food waste is assumed to be sent to AD.

CURRENT CONTEXT

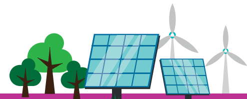
BASED ON TODAY'S CURRENT TECHNOLOGY CONTEXT

80% DECARBONISATION

BASED ON THE COMMITTEE ON CLIMATE CHANGE'S MODELLING OF AN 80% REDUCTION IN EMISSIONS

NET ZERO EMISSIONS

BASED ON THE COMMITTEE ON CLIMATE CHANGE'S MODELLING OF A NET ZERO FUTURE IN 2050, SUPPLEMENTED WITH OTHER PREDICTIONS



CLIMATE-OPTIMISED AD SCENARIO

Environmentally preferable alternative uses to AD feedstocks are maximized, with only remaining feedstocks used for AD.

Hence, no crops are sent to AD. Food waste is assumed to be reduced by 50%, against a 2015 baseline and as a percentage of all food waste (both edible and inedible), and some food surplus currently going to animal feed is assumed to be prevented – with remaining food waste going to AD.

It was also assumed that the law was reformed in this scenario to allow food surplus from catering and containing meat to be sent to non-ruminant animal feed after being safely processed. The same level of manure is sent to AD as in the Industry-driven scenario, except in the net zero context where this is roughly halved.

The scenarios yield very different environmental outcomes in each decarbonisation context because of the different 'counterfactuals' assumed in each context – that is, which alternatives the various processes are replacing. For example, the emissions savings of AD will be different if the biogas generated is assumed to replace the UK's current energy mix (which contains many fossil fuels) or if it is assumed to replace the UK's assumed future energy mix (which will hopefully be generated almost entirely from renewable energy).

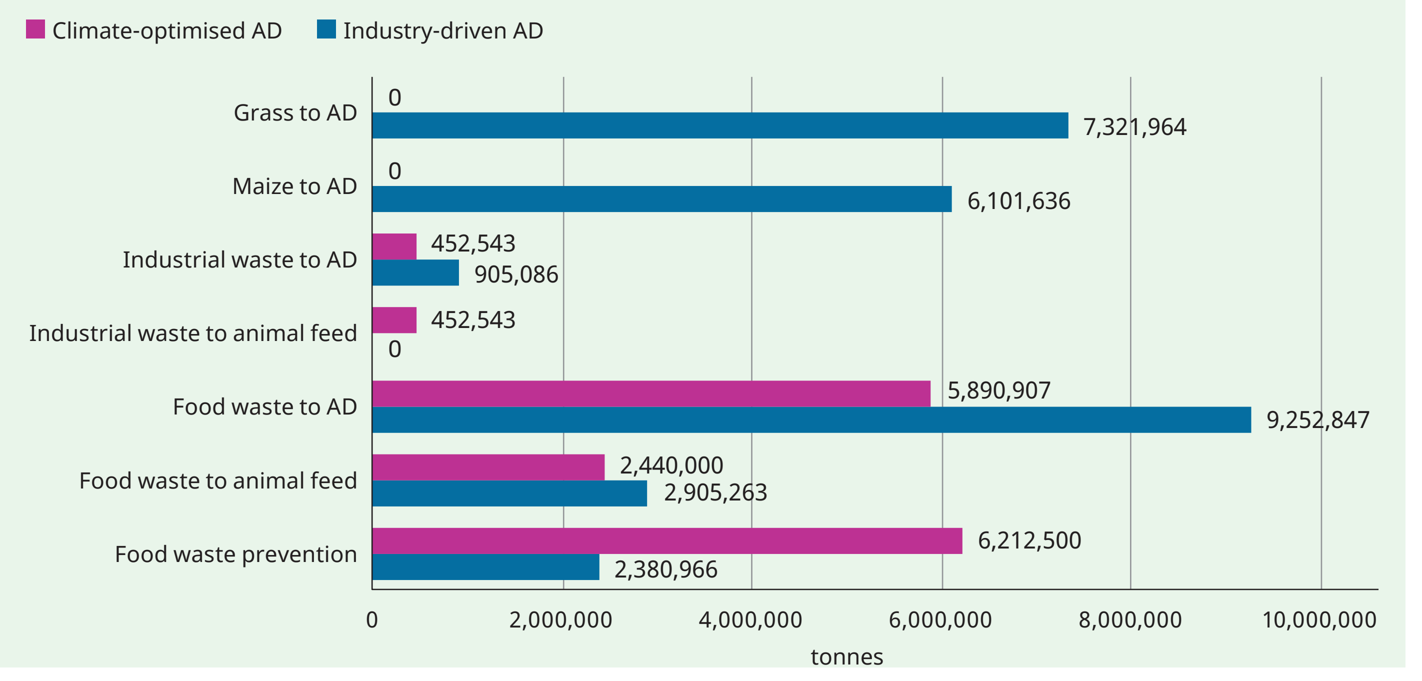
The assumptions used in each scenario and context are too numerous to list here – for more detail on the assumptions made, see Styles *et al.* (2020).

Figure 2 shows the difference in feedstock destinations for the Industry-driven AD and Climate-optimised AD scenarios in all contexts. In the Climate-optimised AD scenario, fewer feedstocks are sent to AD because resources (like food waste or agricultural land) are assumed to be used for more environmental purposes, such

21 In the original LCA, the 'Industry-driven AD' scenario is instead named 'AD-max', and the 'Climate-optimised AD' scenario is instead named 'Circular economy'.

as using the land to grow food or trees, or preventing food waste from arising in the first place. Equal volumes of animal slurry are assumed to go to AD in both scenarios, so these figures are omitted for ease of reference.

Figure 2: Comparison of AD feedstock volumes (tonnes) in industry-driven AD and climate optimised AD scenarios for all decarbonisation contexts



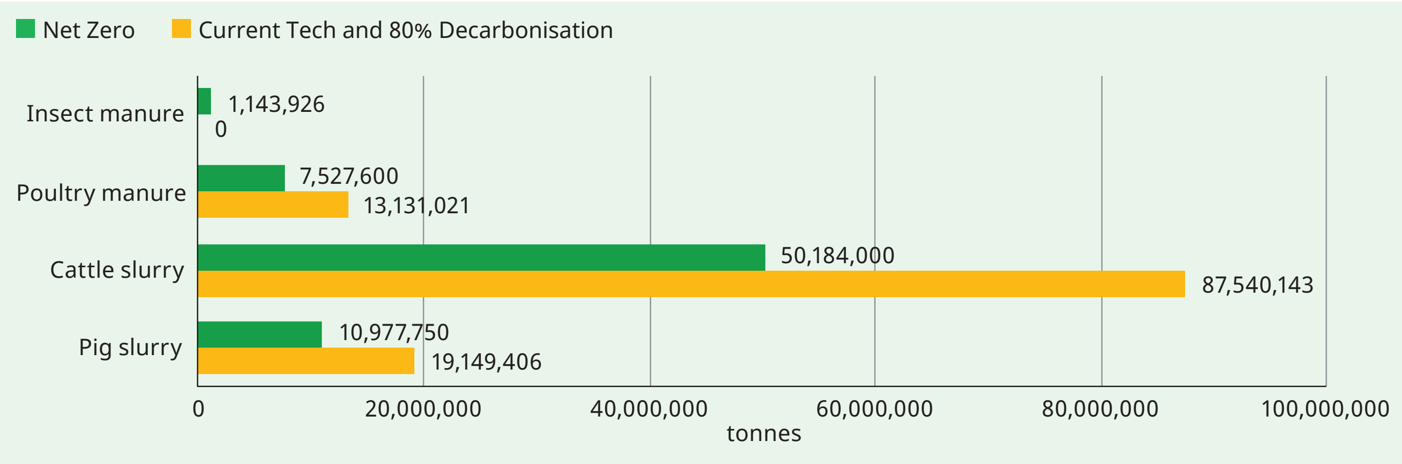
In the net zero context, there are two additional differences:

- Livestock production in the UK is assumed to halve because there is broad scientific consensus that this is crucial for a food system that feeds the global population within planetary boundaries (Bajželj, 2014a; Milner *et al.*, 2015; Aleksandrowicz *et al.*, 2016; Godfray *et al.*, 2018; Willett *et al.*, 2019), with an associated reduction in slurries available to send to AD feedstock in both the industry-driven AD and climate optimised AD scenarios. (See the Manure and Slurry to AD section for more details.)

- Additional food waste from the household level is assumed to be sent to feed for insects[22] in the climate optimised AD scenario only, with the manure produced from these insects subsequently sent to AD. This means that an extra 1,776,860 tonnes of food waste goes to insect feed instead of AD in the climate optimised AD scenario in the net zero context.

22 Using food waste as feed for insects has been found to have environmental benefits by several authors (van Zanten *et al.*, 2015; Smetana, Schmitt and Mathys, 2019).

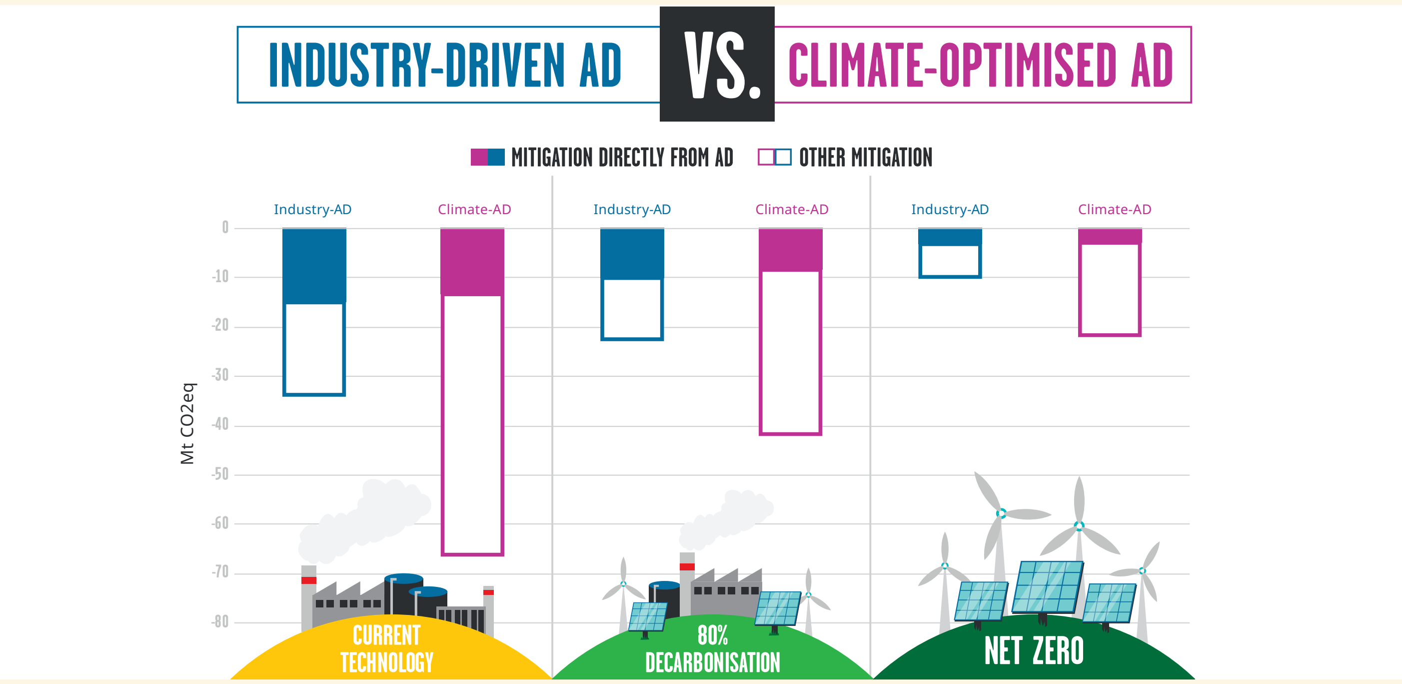
Figure 3: Volume of slurries and manure (tonnes) sent to AD in climate optimised AD scenario in different decarbonisation contexts



FEEDBACK'S FINDINGS

The comparative GHG mitigation achieved by the industry-driven AD vs the climate-optimised AD scenarios is shown for each for the decarbonisation contexts in Figure 4 below. **The climate-optimised AD scenario achieves roughly twice the emissions mitigation of the industry-driven AD scenario**, with AD responsible for the minority of emissions mitigation in all scenarios and contexts. Please note that absolute GHG mitigation is smaller in the future contexts because in these contexts we emit less GHG overall.

Figure 4: GHG mitigation in industry-driven AD vs climate-optimised AD scenarios in different decarbonisation contexts



Allocating land and resources to the more sustainable purposes of the climate-optimised AD scenario – which involves significantly fewer feedstocks being sent to AD – results in far better environmental outcomes. For instance, 43% less food waste goes to AD in the climate-optimised AD scenario compared with the industry-driven AD scenario, and no crops go to AD in the climate-optimised AD scenario.

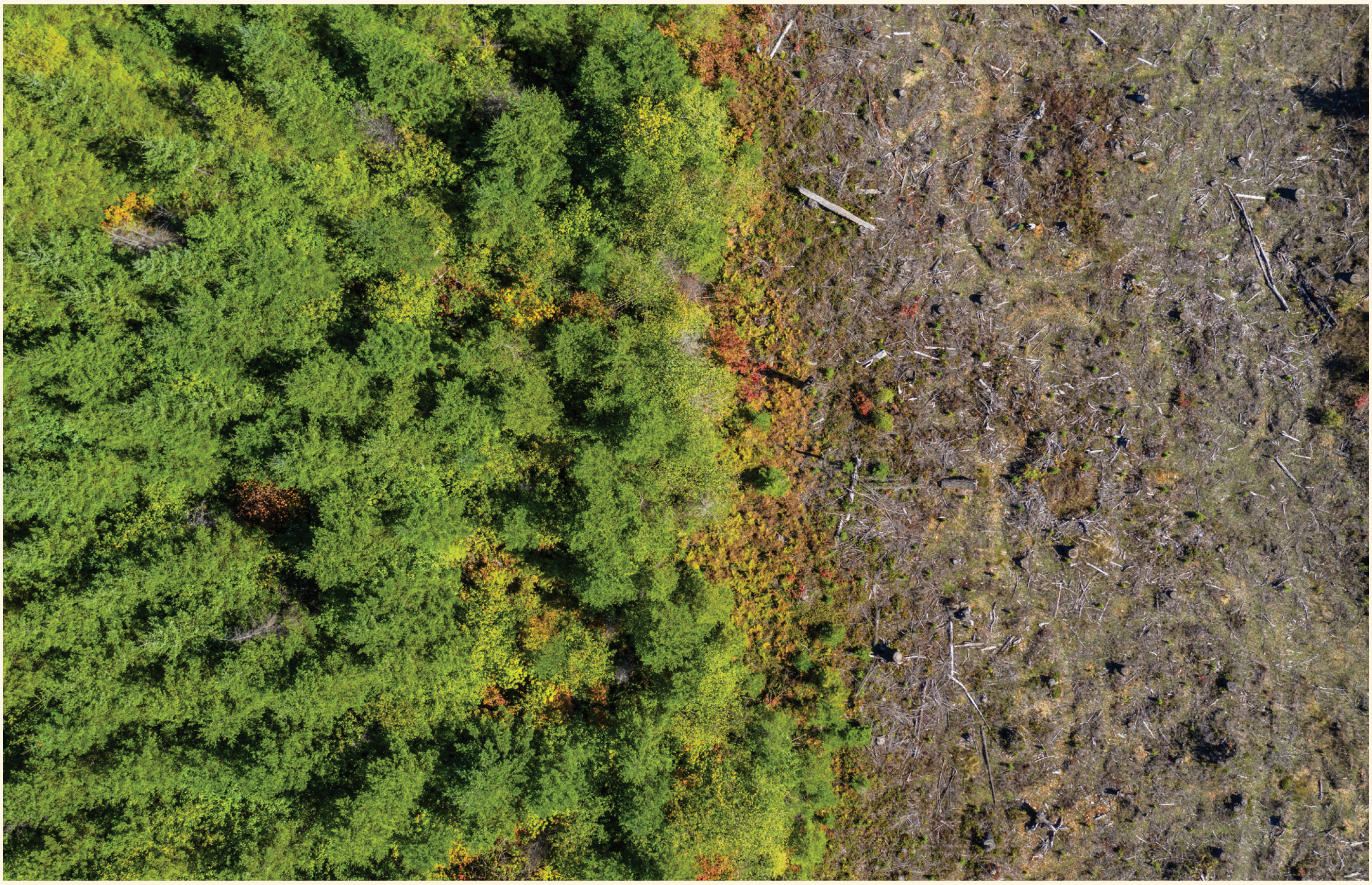
In the current tech context, the **climate-optimised AD scenario achieves roughly twice the GHG mitigation of the industry-driven AD scenario** – 66.9 $MtCO_2eq$ (or 15% of the UK's total national emissions) compared with 34.4 $MtCO_2eq$ (or 7.7% of the UK's total national emissions). These scenarios assume afforestation of grassland freed up by food waste prevention and not used to grow grass directly as an AD feedstock. In the climate-optimised AD scenario, this is equal to 3.2 million hectares of grassland (3 million from food waste prevention and 0.2 million from not producing grass directly as an AD feedstock), compared to only 1.05 million hectares of grassland saved in the industry-driven AD scenario. **The climate-optimised AD scenario would also free up roughly 1.16 million hectares of cropland**[23].

In the climate-optimised AD scenario, halving food waste – and afforestation of the grassland spared by this – alone mitigates approximately 51 million tonnes CO_2eq – about 11.3% of the UK's current total emissions, more than the emissions from the entire UK's domestic agriculture sector. This is made up of 13.6 million $MgCO_2e$ of direct emissions savings, plus 3 million hectares of grassland spared which if afforested would result in an additional 37.4 million $MgCO_2e$. The vast majority of these emissions savings come from prevention, with some from diversion of food waste to animal feed – sending food waste to AD does not count as food waste reduction.

In the industry-driven AD scenario, AD mitigates only 14.9 $MtCO_2eq$ per year directly, with a colossal 81% of these savings coming from manure and slurry feedstocks – primarily because a far higher volume of manures and slurries were assumed to be sent to AD than crops or food waste were. This total mitigation is around 3.3% of the UK's 2018 emissions (451.5 $MtCO_2eq$) – which is significantly lower than ADBA's estimation that AD has the potential to mitigate UK emissions by up to 6% (Whitlock, 2019), even though our study assumes almost all UK manure and slurry is sent to AD[24]. The other emissions savings result from other shifts assumed in the industry-driven AD scenario which are unrelated to AD, like some food waste prevention.

23 0.62 million hectares from food waste prevention, and the rest freed up by not producing AD crop feedstocks and not producing crops grown for animal feed (replaced with food waste based 'eco-feed').

24 ADBA also factor in emissions savings from some other feedstocks such as sewage and green waste, which are not modelled here – however, much of the UK's sewage is already treated by AD, and ADBA predict that only minor emissions savings will result from treatment of green waste (ADBA, 2020a, p. 12), so this should not significantly affect the comparability of results.



Ink Drop, Shutterstock.com

In the 80% decarbonisation and net zero contexts, the climate-optimised AD scenario achieves about twice the emissions mitigation of the industry-driven AD scenario in the 80% decarbonisation context (42.4 MtCO_2eq compared to 23.3 MtCO_2eq), and more than twice the mitigation of the industry-driven AD scenario in the net zero context (22.3 MtCO_2eq compared to 10.5 MtCO_2eq). The more ambitious the level of decarbonisation, the smaller the absolute amount of GHG saved in both scenarios. What matters is that in all contexts, using AD only as a last resort is the most desirable option by a considerable margin. The difference is starkest in the net zero context, showing how important it is to avoid putting most of our eggs in the AD basket when planning future UK energy generation. In the net zero context, the share of mitigation achieved by AD is only 13% of total emissions mitigation in the climate-optimised AD scenario (2.8 MtCO_2eq out of 22.3MtCO_2eq total mitigation), indicating that AD has a diminishing role in mitigating emissions in a sustainable future. As noted previously, this is principally because the vast majority of emissions savings from AD in the current tech and 80% decarbonisation contexts come from manure and slurry feedstocks – whereas in the net zero context, the availability of manures and slurries is restricted because dietary shifts are assumed which lead to a roughly 50% reduction in UK livestock production.

BOX 2: LAND TO SPARE – AFFORESTATION, REWILDING AND FOOD PRODUCTION

Very large areas of land could be freed up for other uses through environmentally preferable alternatives to AD, like preventing food waste, dietary shifts away from meat consumption, and no longer growing maize for AD plants. What are the best possible uses for this land?

Afforestation has significant potential for carbon sequestration (Bastin *et al.*, 2019). There has been a steep decline in tree planting in the UK. Levels in the 1970s and '80s were roughly 2–4 times the scale of tree planting in the last decade, and almost all recent planting has occurred in Scotland (Committee on Climate Change, 2018, p. 39). More carbon sequestration from tree planting is desperately needed, although the capacity of terrestrial ecosystems to store carbon is finite, so this is not a substitute for drastic cuts to fossil fuel emissions (Mackey *et al.*, 2013). Grasslands are generally better suited to tree planting due to their large area, which will make reducing land-intensive beef, lamb and dairy production important.

Feedback's LCA study shows that **in the current technology context, the climate-optimised AD scenario spares an extra 2.14 million hectares of grassland and 700,000 hectares of cropland compared with the industry-driven AD scenario**. This is the result of a combination of preventing food waste, diversion of food waste to animal feed, and no longer growing maize or grass as AD crops (the effects of dietary shifts to plant protein are only modelled in terms of manure availability). If the spared grassland is afforested, **this land could sequester an extra 25.9 million tonnes CO_2eq per year compared with the industry-driven AD scenario**. It should be noted that the calculations for this study assume that the land spared is afforested. Thus, there may be trade-offs between higher-density tree monocultures, which are likely to result in faster carbon mitigation potential, and more biodiverse woodlands, which are likely to have slower and more variable sequestration effects but be more beneficial for wildlife. More studies are needed to look into the best options available – but since time is of the essence, the best approach is to start ambitious tree planting efforts now, using a diversity of techniques so that the differences can then be studied.

Brexit presents the UK with the opportunity to rethink its food production. The Covid-19 outbreak has highlighted the vulnerability of UK food security to disruptions in international food supply chains – at a time when only 52% of the UK's fresh vegetable supply and 17% of its fresh fruit supply are produced domestically (Defra, 2019a, p. 49). Ensuring the area of croplands dedicated to growing food is maximised is especially important if the UK wants to be more self-sufficient in fruit and vegetables, and grow more plant-based proteins – which makes it important to reduce land areas used to grow energy crops and animal feed.

Feedback's LCA study modelled the potential food production possible on the cropland spared in the climate-optimised AD scenario if all of this land were used for food production instead of afforestation. **In the current technology context, total cropland spared in the climate-optimised AD scenario would be enough to produce an extra 7.09 billion kcal and 205 million kg of protein per year, compared with the industry-driven AD scenario.** This would be **enough to provide the recommended intake of calories for 8.6 million people for a year – more than the 8.4 million people currently struggling to get enough to eat in the UK** (Sustain, 2016), and roughly 10% of the UK population. **In the net zero context, the climate-optimised AD scenario would still produce an extra 3.18 billion kcal and 92 million kg of protein per year, compared with the industry-driven AD scenario – enough to feed 3.88 million people for a year**. The AD industry's claims that AD "contributes to food security" (ADBA, 2020a, p. iii) thus do not seem to stack up, compared with better alternatives.

DIFFERENT AD FEEDSTOCKS

When AD plants use different input materials ('feedstocks') – such as food waste, manures and slurries, and crops – to generate energy and digestate, this results in different emissions savings and land use impacts[25]. Per tonne of AD feedstock in the current technology context, food waste saves the most emissions, followed by chicken slurry, then maize, then pig and cattle slurry, then grass. In the two future decarbonisation contexts, the emissions mitigation from sending all feedstocks to AD declines, often significantly – with even the highest mitigation from food waste only leading to -66kg CO_2eq per tonne in the net zero context. This is largely due to the assumed lower GHG intensity of future electricity and heat generation, and fertilisers, which AD products (like biogas and digestate) replace.

Figure 5: Emissions mitigation from sending different feedstocks to AD in current technology and net zero contexts (per tonne of feedstock)

In the sections that follow, the report examines in more detail the environmental impact of different AD feedstocks – that is, different organic materials fed into AD plants to produce energy, gas and digestate – and evaluates where there might be more sustainable alternatives to AD.

25 Other feedstocks are used for AD – like sewage waste and green garden waste. However, we focus here on some of the more environmentally questionable AD feedstocks.

5. ENERGY CROPS AND CROP RESIDUES TO AD

Credit: Varga Jozsef Zoltan / Shutterstock.com

It is well established that using so-called 'energy crops' directly as biofuels is problematic. Biodiesel made from rapeseed, and bioethanol made from barley emit roughly 20% more CO_2 than diesel or petrol (Herman, Mayrhofer and Mayrhofer, 2016, p. 7), while simultaneously encroaching on UK land which was previously used to graze animals or grow crops for human consumption, putting upward pressure on food prices. In a similar manner, growing crops for AD has raised serious concerns about sustainability. Crops used for biogas generally lead to higher eutrophication, acidification and land use than fossil fuels (Hijazi *et al.*, 2016), and although they do lead to some emissions mitigation, there are considerable limits to this, as will be explored in this section.

One of the foremost concerns with crops grown for AD is that they risk diverting valuable agricultural land which could be used to grow food – for this reason, they are often not considered a viable feedstock for AD by policymakers and academics (Paolini *et al.*, 2018). This issue is referred to as **indirect land use change**, which occurs when the cultivation of crops for biofuels and biomass displaces traditional production of crops for food and feed. As farmers worldwide respond to higher crop prices in order to maintain the global balance of supply and demand for food, pristine lands are cleared for agriculture to replace the food crops that were diverted to biofuel production elsewhere.

In 2017/18, approximately 35%, or 4.3 million tonnes, of AD feedstocks were derived from crops, with 3.8 million tonnes of these being crops purpose-grown for AD, and the remainder crop waste (Defra, 2019c, p. 29). In 2018 in the UK, 57,000 hectares were used to grow maize for AD (about 25% of the total area for maize in the UK, equal to 1% of the UK's arable land), plus an unknown hectarage of grass and oilseeds (Defra, 2019c, p. 30). This means the actual total hectarage could be significantly higher as grass production is more land extensive[26]. This compares to the only 116,000 hectares of land used for the production of all UK vegetable crops, and 35,000 hectares used for all fruit crops (Defra, 2019a, p. 6). ADBA claims that "Growing crops for AD in the very highest scenarios would still only use under 1% of the UK's agricultural land" (Tatum, 2017), yet its own projection predicts AD's use of crops roughly doubling by 2032 (ADBA, 2018, p. 16), which would constitute at least 2% of UK arable land plus an unknown area for grass and oilseeds. ADBA even makes the extraordinary claim that agricultural intensification and food waste reduction will shrink the amount of land needed for food production in future, liberating plenty of extra land for massive expansion of bioenergy crops (ADBA, 2020a, p. 16). This position is completely untenable in a global context where agricultural land is expanding into vital ecosystems like forests (driven mainly by a worldwide increase in meat consumption). The UK is already reliant on food imports, and more extensive agro-ecological farming will be required to save the planet's soils. Feedback's LCA findings show that land spared by food waste prevention would be far better used for afforestation, solar energy generation or growing food for human consumption.

Harvested maize field with winter ice.
Credit: Franke de Jong / Shutterstock

MAIZE

In 2017, 31% of maize grown in England was for AD – up from 17% just two years earlier (Defra, 2019b, p. 29). If the call by the National Farmers Union (NFU) for an extra 1,000 AD plants by 2020 were to be fulfilled, the total area of maize grown for AD would need to roughly triple compared with 2017 (NFU, 2013, p. 3) – an area of land which could be used instead to grow over 1 million tonnes of wheat or 5.5 million tonnes of potatoes (Farnworth and Melchett, 2015).

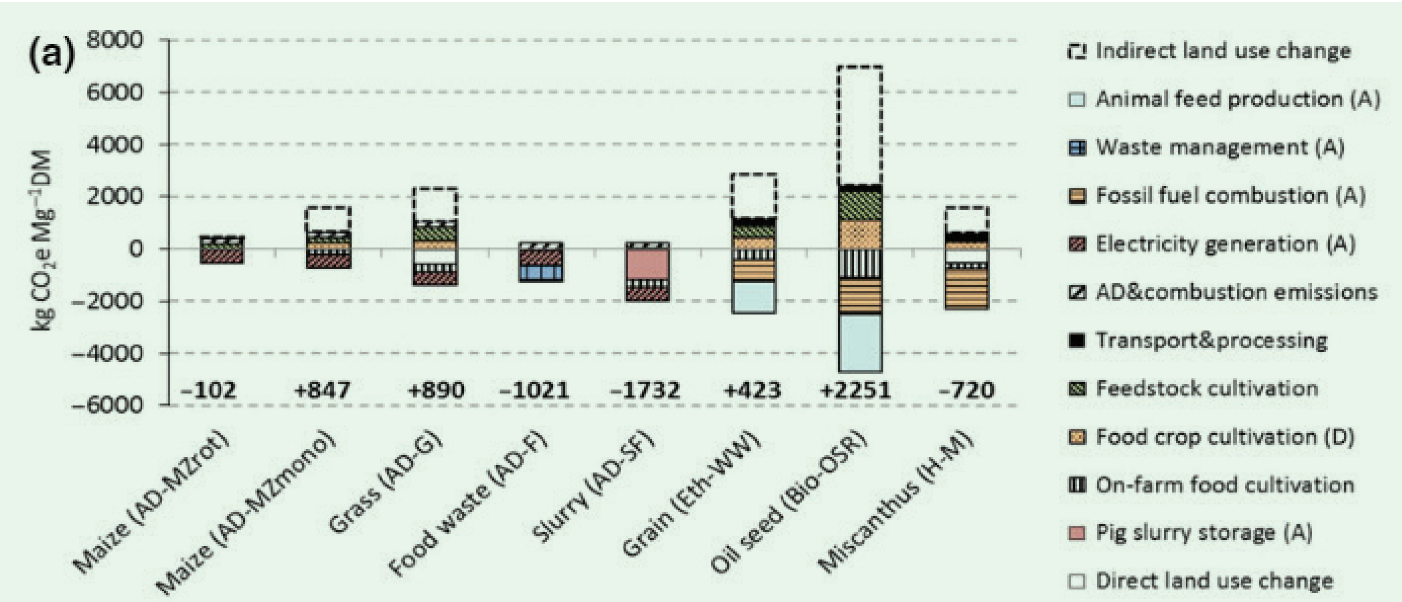
Maize requires heavy pesticide and tractor use, which leaves the soil much more vulnerable to compaction and erosion than other crops (Palmer and Smith, 2013). Maize, like other crops that are harvested late in the year, results in greater soil erosion than crops that are harvested earlier, leading the Soil Association to describe maize as having a "singularly harmful impact" (Farnworth and Melchett, 2015, p. 16).

Several LCAs have illustrated that growing maize for AD can have detrimental environmental outcomes, particularly as a result of its land use requirements (Herrmann, 2013; Purdy *et al.*, 2017; Adams and McManus, 2019). For instance, **one study found that maize monoculture for AD led to net emissions increases of 847 kgCO_2eq per tonne, mainly as a result of indirect land use change** (Styles *et al.*, 2015, p. 1314). The AD industry claims that bioenergy crops can be

26 As average yields for maize in the UK are approximately 37–50 tonnes per hectare, 57,000 hectares should yield about 2.4 million tonnes – meaning that roughly 1.9 million tonnes of grass and oilseed are likely to be unaccounted for in the hectarage taken up by AD crops. Strangely, ADBA claims that only 0.01% of UK arable land is currently used to grow crops for AD (ADBA, 2020a, p. 16), citing the very Defra statistics which say 1% of arable land is used to grow maize for AD alone.

sustainably integrated into crop rotations (ADBA, 2020a, p. 16). However, **although optimal integration of maize into arable rotation leads to negligible food crop displacement and indirect land use change, even in the most efficient systems, it was found to produce only minor emissions savings of -102 kgCO_2eq per tonne**. These emissions savings are far less than savings from using food waste or slurry as AD feedstocks (Styles *et al.*, 2015, p. 1314) (see Figure 6).

Figure 6: Environmental efficiency of bioenergy feedstocks



Source: (Styles et al.*, 2015, p. 1314)*

A key question for future research should be **which crops could replace maize in crop rotation** systems that would earn farmers a similar income, and simultaneously provide valuable nutrition for human consumption rather than being used as an AD feedstock. Since few crops are as bad for the soil as maize, there are many **prime candidates for replacing it in rotation – including most promisingly beans, pulses and vining peas**, which will be essential in the UK's transition to more plant-based diets and have a far better impact on soil quality. Oilseed rape is another alternative.

Biogas production from maize, sorghum and wheat in southern Italy was also found to be unsustainable from a water management perspective, mainly because of the water used in the cultivation phase (Pacetti, Lombardi and Federici, 2015).

Even voices within the AD industry are critical of growing maize for AD. Philip Simpson, Commercial Director of ReFood, whose AD facility in Dagenham is capable of processing more than 160,000 tonnes of food waste every year, said of maize **"Using prime agricultural land to produce energy crops while allowing the landfilling of a far more suitable feedstock like food waste is not sustainable"** (Resource, 2017).

GRASS SILAGE

Grass silage for AD often has lower energy inputs from fertiliser than crops like maize (Hijazi *et al.*, 2016), but it is one of the least environmental feedstocks for AD, mainly because of its large land use. Factoring in indirect land use change, one study found that biogas generation from grass through AD results in a net **increase** in emissions of 890 kgCO_2eq per tonne of dry matter (Styles *et al.*, 2015, p. 1314). Grass is often used as a feedstock alongside manure and slurry, due to its higher energy density and availability near livestock farming. Grasses used for AD are often monocrop grasses grown on land which usually has a high synthetic fertiliser requirement. Grass leys can increase soil carbon in depleted soils (ADBA, 2020a, p. 18), although long-rotation perennial crops and forests are more effective uses of land in this respect.

PERENNIAL CROPS

The **CCC recommendations for planting energy crops make no mention of growing maize, and instead exclusively refer to planting perennial energy crops** like miscanthus, short-rotation coppice (SRC) and short-rotation forestry (SRF), which require very limited fertiliser and can deliver increased soil carbon sequestration (Committee on Climate Change, 2019a, p. 211). This follows a broader trend – the EU is currently moving away from so-called “first generation” biofuels (including maize), and shifting to more sustainable second and third generation biofuels such as miscanthus and SRC (Neslen, 2012; European Commission, 2019). Miscanthus is healthier for soils than maize.

However, **it is highly unlikely that perennial crops would be used as AD feedstocks. Perennial crops like miscanthus and willow are much better suited to use as biomass fuels, such as heat pellets,** which this their main current use (Defra, 2019a, p. 15). It is unlikely that their use as AD feedstocks could be as efficient or widespread as these uses. **Therefore, it seems that the use of energy crops as AD feedstocks has only a limited role or none at all in the CCC’s vision of a net zero future.** This seems to be at odds with ADBA’s assumption that 41% of the land the CCC allocates to growing bioenergy crops should be dedicated to crops for AD (ADBA, 2020a, p. 11).

Some studies have looked at the possibility of using miscanthus as an AD feedstock (Whittaker *et al.*, 2016; Purdy *et al.*, 2017), and miscanthus would be compatible with the current type of AD infrastructure, although it has a lower energy density than maize and would require a longer retention time and more storage. But **even if miscanthus were used for AD, it seems highly unlikely that it would be economically viable at any scale in the UK**. Miscanthus, SRF and SRC grown in the UK **generally result in significant financial losses** (Committee on Climate Change, 2020a, p. 57). **As a result, miscanthus production in England has been minimal for the past decade** – estimated at only 71,000–107,000 tonnes in 2018, about 22% less than in 2009 (Defra, 2019c, p. 14).

FEEDBACK'S FINDINGS

Feedback's LCA study compared the environmental impacts of cultivating one tonne of maize and grass for AD with building solar PV or growing trees on the land used to grow those crops instead.

It found that from the perspective of generating green energy, **solar PV generates 12–18 times more useful energy per hectare than maize or grass grown for AD** (Styles *et al.*, 2020 SI B5). In the climate-optimised AD scenario, using the 319,000 hectares of arable land spared from AD cropping for solar PV electricity generation results in a net additional 454,000 TJ per year of useful energy output compared with the industry-driven AD scenario (Styles *et al.*, 2020 SI B5) – about 8% of total UK energy consumption in 2018 (BEIS, 2019c).

Alternatively, peas are a good candidate to replace maize grown in rotation. **If peas were grown for human consumption on the 282,900 hectares ADBA plans to use for AD crops in its ideal scenario, we estimate this would produce roughly 916,000 million kcal and 76,000 tonnes of protein – enough to feed over 1 million people 100% of their recommended calories per year, including roughly 30% of their recommended protein for a year**, contributing to a shift away from high emissions animal-based proteins.

For tree planting, in the current technology context, **afforestation of land would achieve between 2.6 times (maize) and 11.5 times (grass) more net GHG mitigation than the cultivation of crops for AD biogas production on equivalent land area.** In the 80% decarbonisation context, the emissions mitigation from sending crops to AD remains at roughly the same level, but this relies on bioenergy with carbon capture and storage (BECCS) being introduced to AD plants by this point. BECCS is a speculative technology (see Box 3 in section 'Energy Crops and Crop Residues to AD'), so if BECCS is not deployed, the emissions mitigation potential of crops for AD will decline significantly. **By the net zero context, crop-based AD feedstocks become completely ineffective at emissions mitigation**, even assuming BECCS is deployed at AD plants, with maize resulting in only -20 $kgCO_2eq$ per tonne, and grass actually resulting in positive emissions of +20 $kgCO_2eq$ per tonne of grass sent to AD. This is because AD results in negligible fossil displacement in a decarbonised energy sector, but still leads to soil emissions, methane leakage and digestate emissions. BECCS does not outweigh these difficult-to-avoid emissions, which remain even when the energy sector is largely decarbonised. These results are summarised in Figure 7 and 8 below.

Figure 7: Comparison between net emissions savings of growing crops for AD and using the same land for afforestation instead (per tonne of crop) in the current context

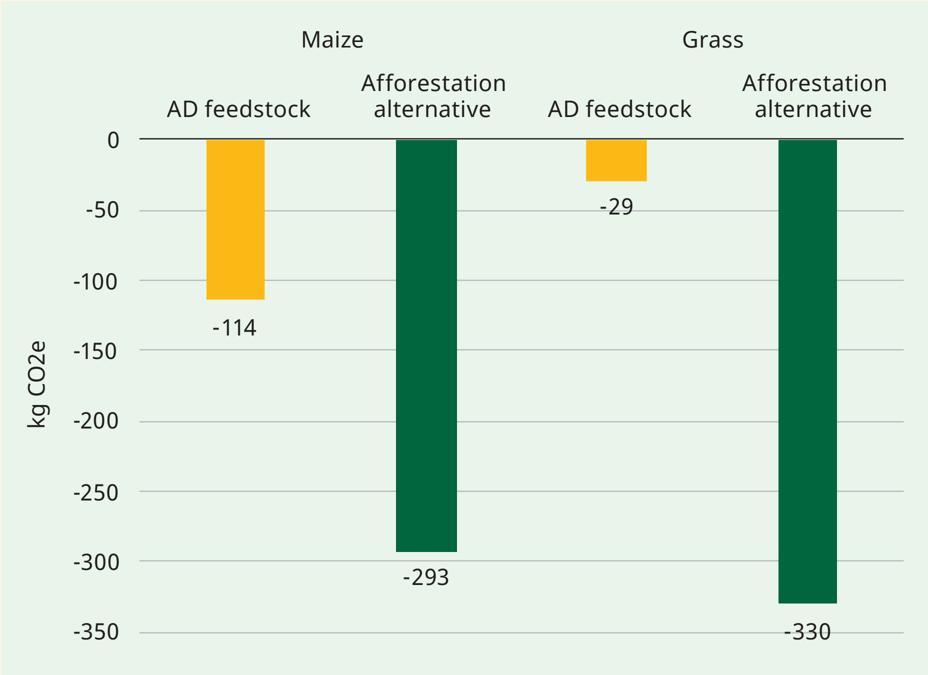
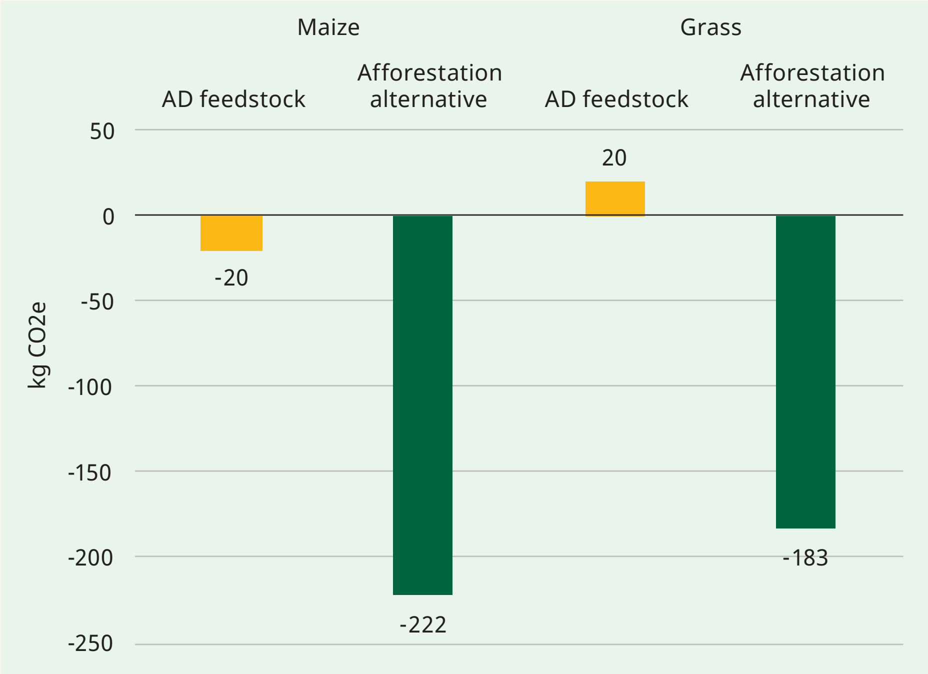


Figure 8: Comparison between net emissions savings of growing crops for AD and using the same land for afforestation instead (per tonne of crop) in the net zero context



BOX 3: WHAT IS BECCS?

BECCS is the process of extracting bioenergy from biomass and capturing and storing the carbon. Most of the IPCC's projections rely significantly on emissions-capturing technologies like BECCS, also known as negative emissions technologies, to offset the emissions still expected to be occurring (Fuss *et al.*, 2014). Yet BECCS is a highly speculative technology which is currently untested at scale (Vaughan and Gough, 2016). This makes relying on BECCS for the bulk of our emissions reductions an extremely risky strategy, and also tends to relieve pressure on more dramatic emissions reductions now because of the assumption that BECCS will offset these emissions in the future. Indeed, many companies from the oil industry to aviation industry have published net zero commitments which involve very few actual emissions reductions and rely primarily on implementing negative emissions technologies like BECCS. This prompts an unavoidable question – if the livestock industry and all these other hard-to-decarbonise industries are relying on BECCS, will it be possible for BECCS to deliver on this scale? Concerns have also been raised about the land required to deploy BECCS at a large scale. Even if considerable emissions reductions are assumed, BECCS would require huge swathes of the most productive agricultural areas or the elimination of over 50% of natural forests for the land needed to offset the remaining emissions (Boysen *et al.*, 2017), also raising the risk of land grabs.

6. FOOD WASTE TO AD

Estimates vary for the amount of food waste going to AD, between 1.9 million tonnes of post-farm-gate food waste (WRAP, 2019b, p. 4) and 3.8 million tonnes of total food waste (Defra, 2019c, p. 28). Food waste thus makes up about 31% of feedstocks for operational AD plants (Defra, 2019c, p. 28), and if the higher estimate is correct, about 32% of the UK's estimated 11.8 million tonnes of food waste goes to AD[27].

Credit: Feedback

PREVIOUS STUDIES

Sending food waste to AD has consistently been found to cause lower emissions than sending it to landfill or incineration (Evangelisti *et al.*, 2014; Edwards *et al.*, 2017), but it also saves substantially fewer emissions than food waste prevention or sending food waste to animal feed.

In 2011, **Defra estimated that food waste prevention saved on average eight times more emissions than sending food waste to AD**[28] (Defra and DECC, 2011, p. 10). A specific comparison with animal feed (Salemdeeb *et al.*, 2017) concluded that using heat-treated food waste in animal feed (wet feed) rated better than sending it to AD on 13 out of 14 environmental indicators, including global warming potential and water pollution[29]. The calculations in the study for the energy needed to render the food waste safe were based on the current UK energy mix.

The table below shows that while diverting food waste from landfill, incineration or compost to AD is beneficial, the benefits are dwarfed by those of **food waste prevention** (equivalent to donation in the table), which **saves 5–25 times more GHG emissions compared with sending food to AD**[30] (Moult *et al.*, 2018a):

27 Combining WRAP's estimated 10.2 million tonnes wasted post-farm-gate and its estimated 1.6 million tonnes wasted at primary production (WRAP, 2019c, 2019b).

28 Using sending the food to landfill as a baseline comparison for both prevention and AD.

29 If renewable energy was used for processing, sending food waste to animal feed (including dry feed) could potentially beat biogas and compost on all 14 indicators.

30 Using 0% emissions mitigation as the baseline, which is roughly equivalent to incineration.

Table 3: Net mitigation as a percentage of embodied food emissions

Disposal option	Food Type					
	Bread	Cheese	F&V	Fish	Meat	Weighted average
Donation	100%	100%	100%	100%	100%	100%
Animal feed	24%	7%	1%	41%	5%	6%
Anaerobic digestion	20%	4%	5%	19%	4%	6%
Composting	3%	1%	-1%	5%	1%	1%
Incineration	11%	2%	-2%	1%	1%	1%
Landfill, 70% CH_4 capture with gas utilisation	-44%	-7%	-12%	-26%	-7%	-10%
landfill, 70% CH_4 capture with flaring	-61%	-10%	-16%	-36%	-10%	-14%
Landfill, 0% CH_4 capture	-227%	-37%	-61%	-136%	-36%	-53%

(Moult et al.*, 2018b Table 7)*

Note: In this table, negative emissions refer to the extra methane emitted by food when it rots in landfill, in addition to the emissions involved in its production[32].

FEEDBACK'S FINDINGS

Feedback's LCA study found that in the current technology context, **preventing food waste results in direct emissions savings approximately nine times higher than sending it to AD** (Styles *et al.*, 2020). This is roughly in line with Defra's findings mentioned above. However, significantly, Feedback went further and modelled the emissions savings of planting trees on the grassland spared through food waste prevention (mainly from avoided beef, lamb and milk waste), and growing food on the cropland spared (through avoiding other food waste). **If food waste is prevented and the grassland used to grow it instead afforested, this results in emissions mitigation levels over 40 times higher than sending the same volume of food waste to AD** (per tonne of food waste)[32]. Additionally, the cropland saved could produce large volumes of food to improve the UK's food security.

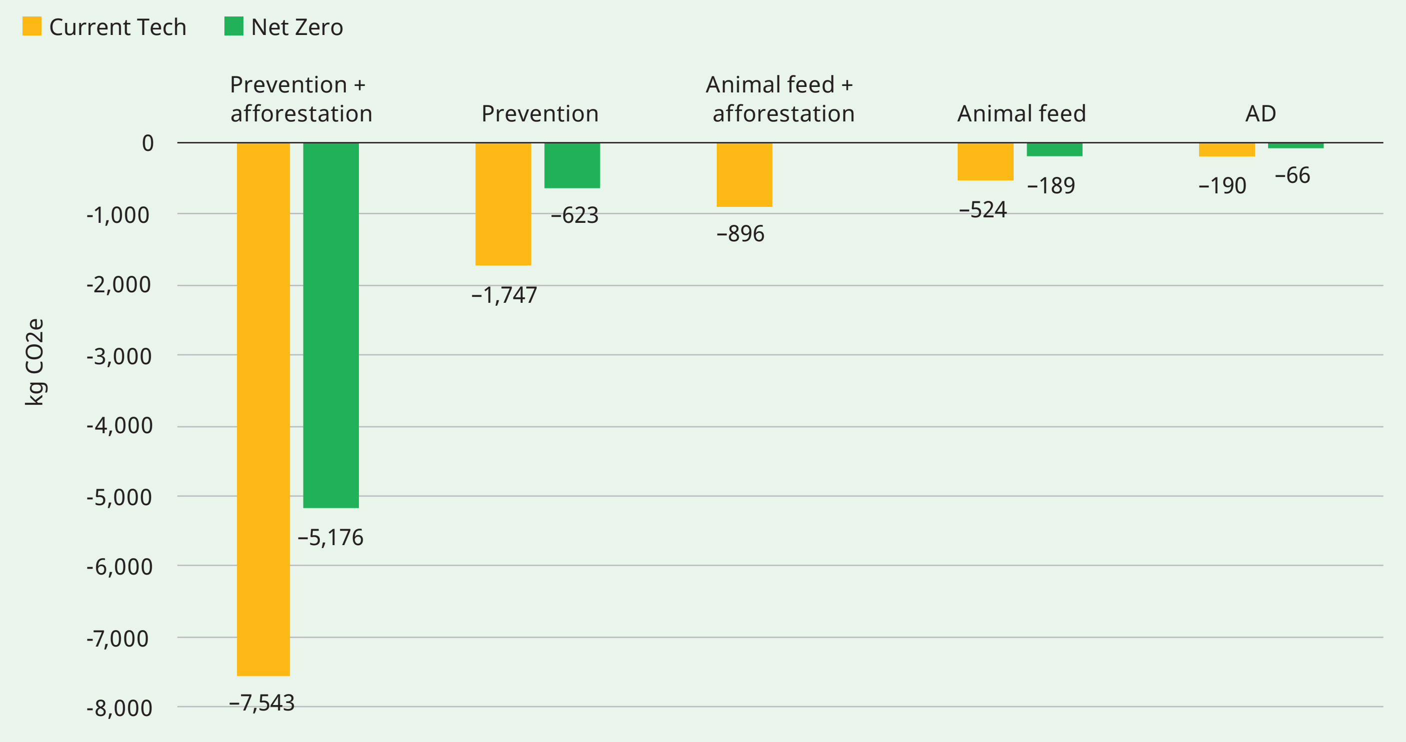
31 In 2014, the methane capture rate for UK landfills was estimated at 55–85% for most operational sites (Defra, 2014), so would be closer to the emissions outlined in the 70% CH4 capture scenarios. This means that even where food is diverted from landfill to AD, the emissions mitigation is fairly limited, and still far worse than donation/prevention. Only a third of the UK's post-farm-gate food waste went to landfill in 2019, with the other two thirds and most food waste on farms at least composted or incinerated (WRAP, 2019b).

32 Emissions savings are calculated on the basis of avoided emissions from production of the food, and do not factor in additional methane emissions avoided from food rotting in landfill. This is because the calculations assume avoidance of landfill as a bare minimum, so the emissions savings are roughly equivalent to those that would be made if food waste were diverted from incineration to prevention, animal feed or AD. For a sense of how this would affect results, see the table above (Moult et al., 2018b Table 7), which lists methane emissions from landfill as extra negative emissions.

In the current technology context, **sending food waste to animal feed saves nearly three times the emissions of sending it to AD** – with additional cropland saved for food production. If cropland previously used to grow animal feed is instead planted with trees, sending food waste to animal feed saves nearly five times the emissions of sending it to AD. In our main modelling, we assumed land spared from animal feed was used to grow crops, but it is worth bearing in mind the higher emissions mitigation figure as sometimes animal feed imported into the UK is in direct competition with forests.

These results are summarised in Figure 9 below.

Figure 9: Emissions savings by food waste destination in current technology and net zero contexts (per tonne of food waste



In future decarbonisation scenarios, modelled prevention always has significantly better outcomes than sending food waste to AD. For instance, **in the net zero scenario, prevention of food waste with afforestation on the land spared leads to emissions savings roughly 78 times higher than sending it to AD** (-5,176 compared with -66 kgCO_2eq per tonne), and even without afforestation saves over nine times the emissions.

Feedback also modelled that halving UK food waste (with afforestation of the 3 million hectares of grassland spared) would save and offset approximately 51 million tonnes CO_2eq (Styles *et al.*, 2020)[33] **– about 11.3% of the UK's current total GHG emissions**, which were 451.5 $MtCO_2$eq in 2018 (BEIS, 2020). It would **also save 0.8 million hectares of cropland. If potatoes and peas were cultivated on this cropland, it could produce 15.1 billion kcal of food – enough for the daily needs of 18.5 million people – including 440 million tonnes of protein**. In a net zero context, halving food waste still saves a significant 18.15 million tonnes CO_2eq, which would be about 21.6% of the projected gross emissions still occurring in our modelled net zero future, so reducing food waste would still have a very significant role to play. This stunning finding reveals the central importance of reducing food waste to the UK's ability to meet its Paris climate agreements. It is important to highlight here that Feedback is using a more ambitious interpretation of halving UK food waste in our climate-optimised AD scenario (a 50% reduction of all food waste from farm to fork, against 2015 baselines, facilitated by greater regulation of food businesses) compared with the interpretation used by businesses under WRAP's voluntary agreements (a 50% reduction of only edible food waste, against 2007 baselines, largely excluding primary production food waste). Therefore, **using current less ambitious voluntary approaches**, as modelled in the industry-driven AD scenario, **would yield far fewer benefits – resulting in 63% lower emissions mitigation and a 43% lower yield of calories and protein. If spared land is not used for afforestation or crop production** (e.g. if the government does not plant trees on all the grassland spared, or the AD industry's proposal to grow bioenergy crops on the spared cropland is realised), **then emissions mitigation and extra food production would be even lower**. The AD industry currently assumes the pace of change established by WRAP's voluntary approach to food waste prevention.

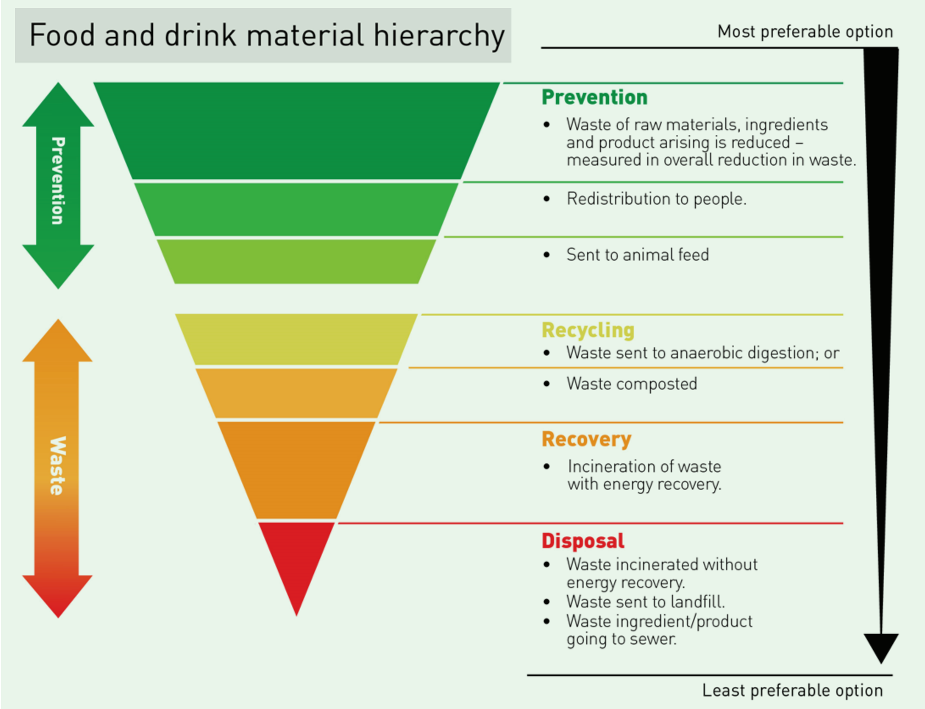
It is vital to note that **this climate-optimised AD scenario involves a significant restriction of the food waste available for AD**, with food waste 'reduction' achieved primarily through prevention complemented with some extra food waste diverted to animal feed. For more detail, see the Finding the 'Sustainable Niche' for AD section and also (Styles *et al.*, 2020).

INCENTIVISING THE FOOD WASTE HIERARCHY

These conclusions are broadly consistent with the most established food waste hierarchies which, in reporting towards SDG 12.3 (Hanson, 2017), class AD as a less environmental destination, and categorise food sent to AD as food waste (not as a 'reduction'). In contrast, sending food for human consumption or to animal feed counts as food waste reduction, and towards SDG 12.3 – with the cut-off point occurring above AD, as shown in Figure 10 below.

33 In the current technology context – this scenario assumes a 50% reduction in the sum total of edible and inedible food waste across the whole UK supply chain (this sum total is 10.2 million tonnes + the estimated 1.6 million tonnes wasted on farms) against a 2015 baseline. It also assumes some movement of food surplus up the food waste hierarchy from animal feed to prevention. This differs from the UK's current voluntary targets under WRAP's Courtauld 2025 and Food Waste Reduction Roadmap schemes. These target a 50% reduction by 2030 in edible food waste only, using baseline years of 2007 onwards to measure reductions, and currently exclude primary production food waste from reduction targets due to lack of data, with no specific targets for food surplus prevention. For more detail on the modelling used, see (Styles *et al.*, 2020).

Figure 10: Food and drink material hierarchy



(WRAP, 2019b, p. 3)

The proportion of the UK's food waste going to AD/composting at each stage of the supply chain is shown in Figure 11 below.

Figure 11: Summary of food surplus, waste and related material arisings in the UK, and their respective treatment and disposal routes

	Household	HaFS*	Retail & Wholesale	Manufacturing	Farm	Total[1]
Total food waste	7.1 Mt	1.0 Mt	0.3 Mt[8]	1.85 Mt	nk	>10 Mt
Preventing food becoming waste: Food (excl. inedible parts	5.0 Mt (£15.0 bn)	0.75 Mt (£2.9 bn)	0.3 Mt (£0.8 bn)	0.95 Mt (£1.4 bn)	nk	> 7.0 Mt (>£20 bn)
Redistribution & animal feed	0.3 Mt [n/a humans 0.3 Mt pets/ other animals	>0.001 Mt [>1kt to people [n/a to animals]	0.04 Mt [17.5kt to people] [27kt to animals]	0.65 Mt [23kt to people] [635kt to animals]	nk	> 1.0 Mt
Waste management: Recycling (AD/composting)	1.2 Mt[2]	0.04 Mt	0.15 Mt[3]	0.54 Mt[4]	nk	> 1.9 Mt
Recovery (energy from waste, landspreading)	2.7 Mt[5]	0.62 Mt[6]	0.15 Mt[3]	1.3 Mt[4]	nk	> 4.8 Mt
Disposal (sewer, landfill, incineration w/o energy recovery)	3.2 Mt[5] [1.6 Mt sewer 1.5 Mt landfill <0.1 Mt incineration]	0.36 Mt[6] [nk sewer 0.35 Mt landfill 0.01 Mt incineration]	nk[5]	0.002 Mt[4] [nk sewer 0.002 Mt landfill]	nk	> 3.5 Mt
In addition:						
Rendering of animal by-products				0.6 Mt	nk	0.6 Mt
Other food by-products[7]				2.2 Mt		2.2 Mt

* HaFS = hospitality and food service; nk = not known; n/a = not applicable

(WRAP, 2019b, p. 4)

For example, in 2019/20 Tesco generated 77,807 tonnes of surplus food, of which 53% was still sent to energy recovery (mainly AD, with some incineration), much of which is fit for either consumption by humans or animals (Tesco, 2020).

Local authorities in the UK face lower gate fees for the collection of food waste for AD than for collection for in-vessel composting, incineration with energy recovery, or landfill (mainly due to the substantial Landfill Tax) – incentivising AD over disposal methods lower down the food waste hierarchy.

However, the destinations higher up the hierarchy are neglected. Although the UK government uses the food waste hierarchy to prioritise food waste use through voluntary initiatives like Courtauld 2025 and the Food Waste Reduction Roadmap, its current fiscal incentives are disproportionately skewed towards AD, despite it being one of the lower levels of the hierarchy. (The numerous subsidies given to AD were explained in more detail in the Subsidies and Survival section earlier in this report.) As a result of this asymmetry, edible food that is perfectly nutritious and delicious is often sent to AD.

The chairman of the Scottish Tenant Farmers' Association recently condemned the fact that increasing volumes of distillery draff and pot ale syrup, traditionally used as home-grown animal feed protein, have been diverted to AD in recent years – driving Scottish livestock farmers to become more reliant on imported soya (Nicholson, 2020). Waitrose admitted to the House of Lords enquiry into food waste that **"there is a clear temptation, on economic grounds, to prioritise energy recovery over redistribution"** (House of Lords EU Committee, 2013, p. 46). **The enquiry report therefore recommended that incentives for AD should not be allowed to distort the food waste hierarchy** and that the UK government should investigate incentives for food waste redistribution (House of Lords EU Committee, 2013, p. 48). **Food redistribution charity FareShare has long protested this uneven playing field between AD and redistribution** (FareShare, 2017). To remedy this situation, it launched a campaign which successfully led to the government introducing some pots of funding to cover the estimated £150 per tonne it costs to separate, store and transport edible surplus food to charity – with £15 million announced in 2018 (Khan, 2018).

However, **voluntary food redistribution is only a short-term solution to both food waste and food poverty** – people should not have to rely on food banks in one of the richest countries on the planet. The focus should be on designing both food waste and food poverty out of the system in the first place. In line with this, **the government should prioritise food waste prevention over redistribution** – supplying funding and incentives to ensure surplus food is either not produced at all or reaches human consumption instead, either through the market or through guaranteed social safety nets and government services. However, funding to date appears only to have been reducing – for instance, WRAP has seen its government funding from Defra fall from £56 million in 2009/10 to below £10 million in 2017/18 (Reece, 2013; Murray, 2018)[34]. **WRAP and the food industry have prioritised voluntary food waste prevention by businesses over regulatory approaches, despite the slow progress achieved through existing measures and lack of transparency that has resulted** (Bowman, 2020). The UK government should

34 These figures are for WRAP's total work on waste generally, not just food waste.

learn the lessons from such regulatory successes as the plastic bag tax and Landfill Tax – tax penalties and incentives should be structured in such a way as to ensure food is used to its highest potential in the food waste hierarchy, such as by increasing taxes on landfill and incineration.

The AD industry acknowledges the food waste hierarchy, stating that AD should only be used for "inedible" food waste that "cannot be prevented or redirected for consumption by humans or animals" (ADBA, 2020a, p. 8). However, it continues to advocate for increased subsidies and support for AD, which may risk diverting food down the food waste hierarchy, when the industry already receives more funding than activities at higher levels of the hierarchy. **Increasing taxes on incineration and landfill instead would ensure food goes to AD as a last resort, but prevent perverse incentives diverting food from better alternatives, and generate revenue to fund greater food waste prevention.**

Credit: Feedback

CASE STUDY 2: AD PLANT AT A EUROPEAN PORT

Feedback found a striking example of the misuse of AD in research conducted in 2017 (Colbert, 2017). Located next to importers and warehouses at a European port from which it sourced produce, we discovered an AD plant processing fresh edible fruit and vegetables with a market value of hundreds of thousands of pounds every single day. On the day we visited, the following list of (mostly **edible**) food was present at the AD plant ready for processing, and we were informed that the AD facility, at full staff capacity, would process all this food in a single morning:

- 500 kg of broccoli (unknown origin)
- 500 kg of British celery
- 400 pineapples (unknown origin)
- 4 tonnes of cranberries (unknown origin)
- 600 kg of spinach leaves (unknown origin)
- 200 boxes of Peruvian asparagus (approximately 7,500 asparagus spears)
- 10,000 figs (unknown origin)
- 1 tonne of satsumas and 2 tonnes of oranges (unknown origin)
- 25 tonnes of grapes from Greece, Macedonia, India and South Africa
- 500 kg of yellow plums (unknown origin)
- 200 romaine lettuces (unknown origin)
- 60,000 Spanish cucumbers
- 6,000 boxes of Colombian physalis
- 4,000 cabbages (unknown origin)
- 1 tonne of carrots (unknown origin)
- 1 tonne of tomatoes (unknown origin)
- 800 iceberg lettuces (unknown origin)
- 300 125g punnets of rocket (unknown origin)

7. MANURE AND SLURRY TO AD

In 2017/18, about 16% of feedstocks for operational AD plants were manures/slurries, amounting to about 2 million tonnes (Defra, 2019c, p. 28). To put this in perspective, in 2010, UK livestock manure production was roughly 83 million tonnes (Smith and Williams, 2016).

LCAs have consistently found that sending animal wastes such as manures or slurries to AD has positive environmental effects, including mitigating GHG burdens, compared with traditional manure storage (Hijazi *et al.*, 2016). For instance, deploying AD across all dairy farms with more than 133 milking cows in the UK could achieve "GHG savings as high as 1.8 million tonnes of CO_2e per year" (Mesa-Dominguez *et al.*, 2015, p. 4). Treating pig slurry with AD avoids on average 1,732 kg CO_2eq per tonne of dry matter treated, the highest saving compared with other AD feedstocks considered in this study – primarily as a result of avoided emissions from slurry storage, with avoided electricity generation as the second largest emissions saving (Styles *et al.*, 2015, p. 1314). Biogas produced by AD from manure has also been found to result in emissions savings compared with conventional gasoline (Tonini *et al.*, 2016).

However, the **biogas yield from animal slurries is significantly lower than from other AD feedstocks like crops and food waste**. For instance, the biogas yield for cattle slurry and pig slurry is 15–25 m^3/t and poultry slurry 30–100 m^3/t, compared with 200–220 m^3/t for maize silage, 160–200 m^3/t for grass silage and 276–400 m^3/t for potatoes (Biogas Info, 2020)[35]. This means that **manure is often co-digested with crops to improve its efficiency, so in these cases, the environmental impact of crops for AD and their associated land use must be factored in**. **Slurry-only AD plants may be less economically viable.** A limited number of AD plants in the UK manage to run entirely on manure[36], but these tend to be smaller-scale on-farm ADs mainly supplying electricity and residual heat to the farm itself (Riley, 2017). Many small-scale on-farm AD plants are better suited to electricity production than biomethane upgrading (ADBA, 2020a, p. 19). Since AD is not a particularly sustainable or cost-effective way of producing electricity compared with wind or solar, the question arises – can small-scale AD plants be converted to supply biomethane in a cost-effective way without huge subsidies and reliance on unsustainable crops?

When pig slurry is located further away from the AD plant, transport emissions from delivering these large slurry volumes can considerably reduce emissions savings (Hijazi *et al.*, 2016, p. 1297). Transport costs mean that **AD plants may require a concentration of manure in one area to be economically viable**. For example, one study estimated the economically viable transportation distance was only 10 km for liquid manure compared with 40 km for other agricultural feedstocks with dry matter greater than 70% (Sliz-Szkliniarz and Vogt, 2012, p. 755). **This may mean that slurry-only AD plants inadvertently incentivise concentrated intensive farming systems**.

The CCC modelling for reducing emissions from agriculture and land use by 2050 assumes an "increase in the uptake of anaerobic digestion to treat 10–20% of cattle, pig and poultry waste by 2050" (Committee on Climate Change, 2018, p. 38). This is significantly lower than the levels which ADBA and the NFU would like to see.

---

35 For more information, see Appendix 3: Biogas Yield of Different AD Feedstocks.

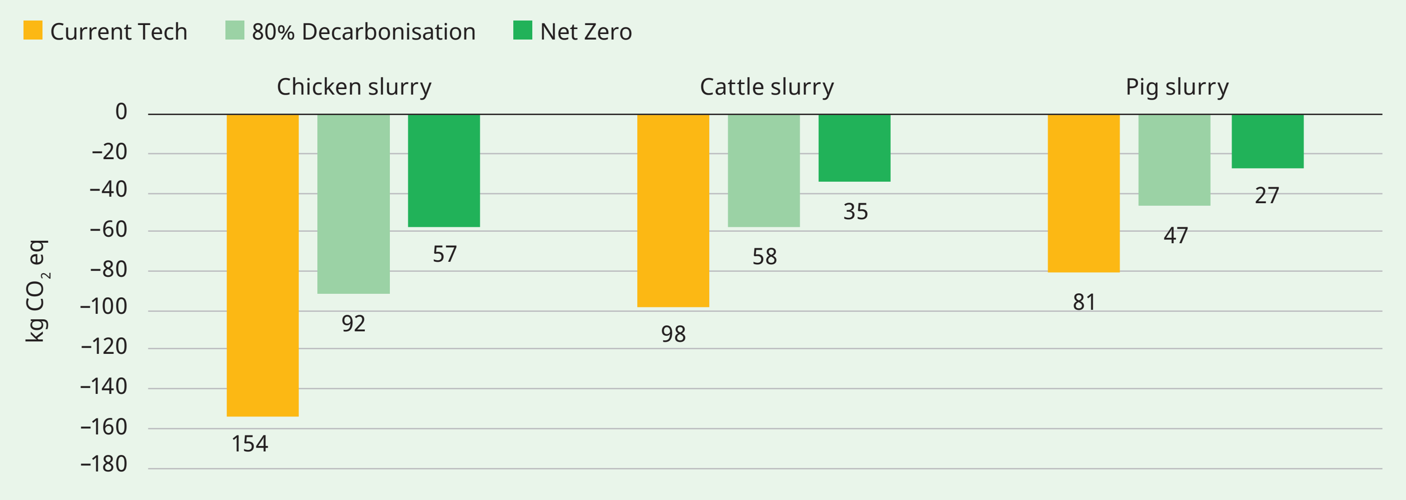
36 18 in 2017, with 20–30 in the planning process (Riley, 2017).

FEEDBACK'S FINDINGS

Feedback's LCA study found that **the majority of emissions savings from sending animal slurry to AD come from avoided manure management emissions** (Styles *et al.*, 2020), rather than because the energy generated from AD displaces a significant amount of fossil fuels. This is partly because, as mentioned previously, manures and slurries have a very low energy density compared with food waste or crops due to their high water content.

The emissions mitigation per tonne of slurry or manure sent to AD declines significantly in more ambitious decarbonisation scenarios – by about two thirds to far lower values, as shown in Figure 12 below.

Figure 12: Emissions mitigation per tonne of manure or slurry sent to AD in different decarbonisation contexts

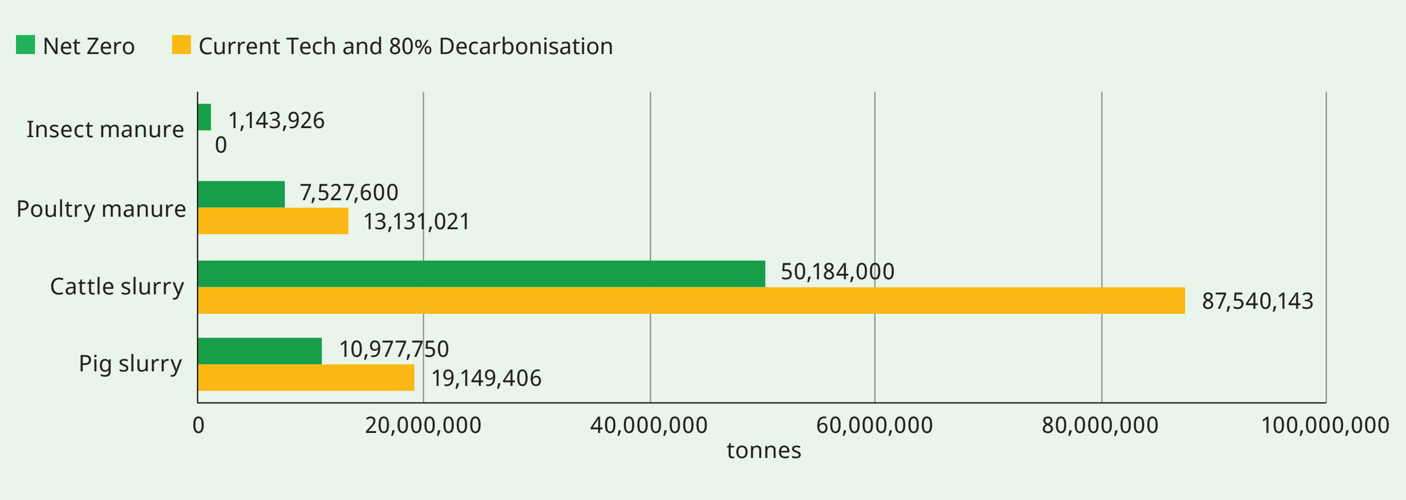


This decline in emissions mitigation mainly occurs because, in the 80% decarbonisation context, a 50% reduction in manure management emissions is assumed due to practices such as covered storage being implemented. Therefore, sending manures and slurries to AD prevents fewer emissions relative to alternative animal waste management options[37]. In the net zero context, the emissions mitigation per tonne is even lower because the manure management emissions and fertiliser manufacture emissions, which AD avoids, are assumed to be lower.

In our study, it was assumed that 87% of slurries and manures from UK livestock were sent to AD in both the industry-driven AD and climate-optimised AD scenarios, except for in the net zero context where the volume of slurries and manures available was assumed to halve, but 100% of this was sent to AD (see Figure 13).

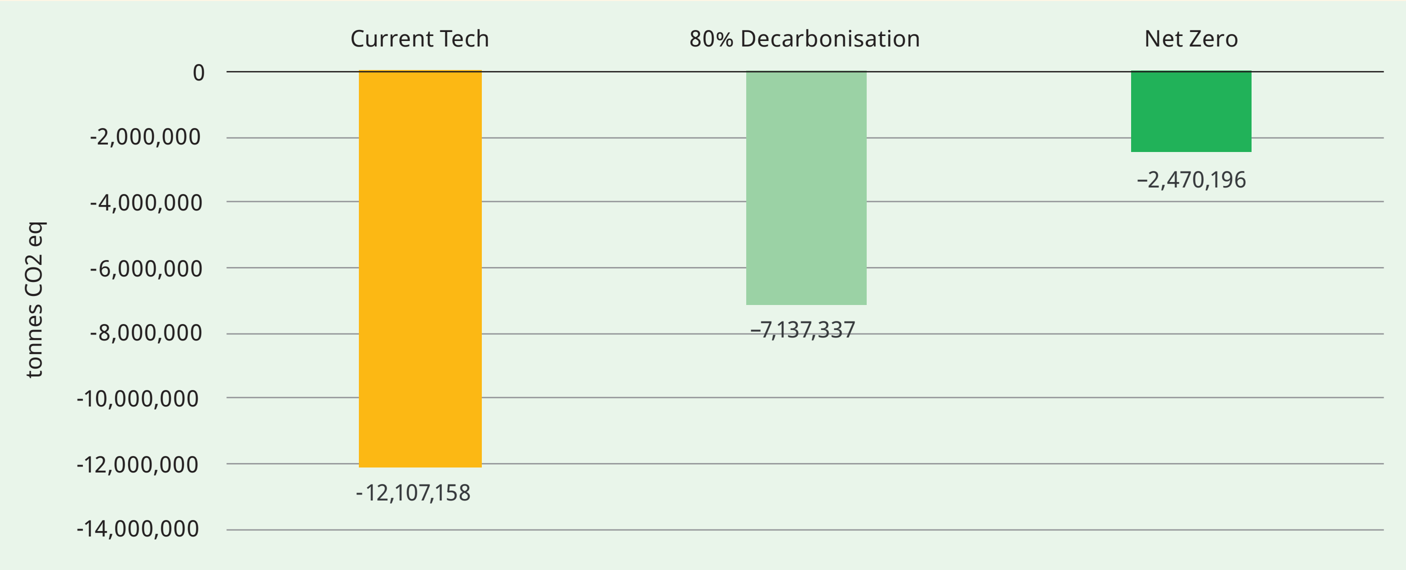
37 It will be a legal requirement for all UK slurry pits and manure heaps to be covered by 2027 to cut ammonia emissions (Tasker, 2018), so this scenario will become the default alternative to AD very soon, reducing the emissions mitigation of AD compared with this default.

Figure 13: Volume of slurries and manures sent to AD in different contexts (tonnes)



The emissions mitigation as a result of sending slurry and manure to AD in the different decarbonisation contexts is shown in Figure 14 below.

Figure 14: Emissions mitigation from sending slurry and manure to AD in different contexts (tonnes CO_2eq)



Since the volumes of slurry and manure produced by UK livestock are so large, the theoretical total emissions mitigation of sending it all to AD is significant. In the current tech context, if this were feasible, **sending nearly all of the UK's manure and slurry to AD could save a strikingly high 12.1 million tonnes CO_2eq, representing 27% of the UK's domestic agricultural emissions in 2018** (BEIS, 2020). **However, sending nearly all slurries and manures in the UK to AD is not only significantly beyond what is projected by the NFU and CCC, but faces serious barriers to its economic viability**. Before AD of slurries can be considered sustainable, the industry must demonstrate how it is possible to overcome these dilemmas of economic viability without co-digesting slurries with significant volumes of unsustainable crops like maize, and without subsidising AD in a way which incentivises expansion of the very industry (livestock) that AD is meant to make more sustainable (see 'When AD incentivises the growth of industrial livestock farming' below). The emissions mitigation from sending slurry and manure to AD is substantially less in the 80% decarbonisation scenario because of the reduced emissions mitigation per tonne mentioned above. In the net zero context, the overall emissions mitigation declines even more. This is because, in addition to the emissions mitigation per tonne decreasing further, the overall tonnage of manures/slurries sent to AD nearly halves due to an assumed 50% reduction in UK meat and dairy consumption in the net zero context, which limits the availability of slurries and manures.

COMPARISON WITH DIETARY CHANGE

There is a scientific consensus that, alongside food waste reduction, dietary change including a cut in meat consumption will be essential to achieve the necessary reductions in GHG emissions related to the food system (Bajželj, 2014b; Kim *et al.*, 2015; Milner *et al.*, 2015; Poore and Nemecek, 2018; Willett *et al.*, 2019). The mitigation potential of AD on livestock production is very limited compared to the savings from dietary shifts to plant protein sources. This is partly because storage and handling of manure represents only approximately 10% of the 7.1 gigatonnes of CO_2eq emitted by livestock supply chains globally per annum (Gerber and FAO, 2013, p. xii). In the UK, wastes and manures make up only about 15% of the total emissions of the agriculture sector, whereas 47% are caused by enteric fermentation in cattle and sheep (Committee on Climate Change, 2019b, p. 187) – and this does not factor in emissions from imported meat or animal feed. The remaining (smaller) mitigation potential from sending slurries to AD comes from its generation of electricity and gas. This declines as the energy grid shifts to renewables.

In contrast, a report commissioned by the CCC estimates that **a 50% reduction in just the UK's beef, lamb and dairy consumption by 2050 could result in a 37% reduction in total domestic emissions from the UK agricultural sector by 2050** (CEH and Rothamsted Research, 2019, p. 29). It would also **free up an estimated 4.2–6.9 million hectares of grassland**[38]. **If trees were planted on 4.2 million hectares**, this would result in an estimated 54 million tonnes CO_2eq annual average carbon sequestration by 2032[39], which (assuming UK agriculture's emissions fall by 37%) would be **enough to offset remaining UK domestic agricultural emissions nearly twice over**[40]. Dietary shifts away from chicken and pork are also very effective. On average, per gram of protein, **switching from poultry meat to tofu results in a 65% reduction in emissions and 69% in land use**, and switching from pig meat to tofu results in a 74% reduction in emissions and 80% in land use (Poore and Nemecek, 2018 Figure 1). More on the urgent need to reduce the scale of big livestock can be found in Feedback's report *Big Livestock versus the Planet* (Feedback, 2020).

38 The estimate of 4.2 million hectares is 50% of the pastureland which Harwatt and Hayek (2019) estimate is currently used for animal agriculture. The higher figure is from the report commissioned by the CCC which compares land use savings relative to a future 'business as usual' scenario where 12.26 million hectares of grassland are assumed to be used for agricultural production by 2050.

39 Extrapolated from Harwatt and Hayek (2019).

40 Based on the UK's domestic agricultural emissions in 2018 – 45.4 million tonnes CO_2eq (BEIS, 2020).

WHEN AD INCENTIVISES THE GROWTH OF INDUSTRIAL LIVESTOCK FARMING

The case of Northern Ireland is a worrying example of AD becoming a driver for the expansion of intensive livestock farming with high levels of emissions. We call livestock farming where manures or slurries are supplied as feedstocks for AD 'energy livestock'.

CASE STUDY 3: INDUSTRIAL LIVESTOCK IN NORTHERN IRELAND

In 2012, the government of Northern Ireland set up the Agri-Food Strategy Board (AFSB) – an industry committee formed to create a "strategic action plan" for agriculture (SourceMaterial, 2018). This was chaired by Tony O'Neill, a senior director at Moy Park (Northern Ireland's biggest employer and a supplier of chicken), and its members included executives from meat processor Dunbia, biogas power generator Linergy, and animal feed producers Devenish Nutrition and John Thompson and Sons (AFSB, 2014) – all people with a stake in the expansion of intensive livestock farming. O'Neill told a Stormont committee in 2014, shortly after he had left Moy Park, that the ASFB is "behind the officials looking at what they are doing in response to our asks" and "will be suitably demanding and critical if they are not doing exactly what we ask them to do" (Committee for Enterprise, Trade and Investment, 2014, p. 8). The **ASFB *Going for Growth* strategy** was launched in 2013 to spur economic growth by intensifying and modernising agriculture (DAERA, 2013a). The plan **set targets to grow the pig sow herd in Northern Ireland by 40% by 2020** to 53,000, increasing mainly export-oriented pig and poultry sales. The plan also recommended the c**onstruction of around 350 poultry houses over 18 months** (DAERA, 2013a, pp. 54–9).

Credit: David Tadevosian

This growth has been realised. By June 2019, the size of the pig herd in Northern Ireland had increased to 674,000 pigs, up 41% from 480,000 in 2013, and the number of poultry had increased by 30% from over 19 million in 2013 to nearly 25 million (DAERA, 2013b, 2020). There has been marked growth in intensive farming, with an associated increase in animal excrement. A prime example is a planning application for an extra 81,000 pigs in the Limavady area, with fattening pigs spread out over separate farms so there are no more than 2,000 per site to ensure nitrate pollution regulations would not apply when spreading slurries on local land (FOE NI, 2018). The project is opposed by local campaign group Stop Limavady Pig Factory, which objects to the nitrate pollution risks associated with the 1.3 million tonnes of pig slurry expected yearly for the whole of Northern Ireland if the *Going for Growth* 2020 targets are met (FOE NI, 2018).

CASE STUDY 3: INDUSTRIAL LIVESTOCK IN NORTHERN IRELAND (CONTINUED)

AD played a key role in this strategy by helping the rapidly growing farming industry cheaply dispose of the vastly increased amounts of excrement while technically complying with EU regulations. The EU's Nitrates Directive, which places limits on the spread of compounds like ammonia found in animal slurries, was seen as a key barrier to intensive poultry farm growth. The *Going for Growth* strategy highlights that failure to address the problem of "disposal of poultry litter within current environmental legislation [...] threatens the sector's viability" and recommends that "an urgent solution" should be sought (DAERA, 2013a, p. 54).

In 2013, the Northern Ireland government created "a dedicated team of officials" to help Moy Park expand and "meet its EU obligations under the nitrates directive". This team met between 2014 and 2017 to discuss the feasibility of AD as a solution to the problem (SourceMaterial, 2018). According to speaking notes prepared for the head of the Northern Ireland Department of Agriculture, Environment and Rural Affairs (DAERA), **the government's introduction of high subsidies for AD was "an indication that Government is highly supportive of sustainable solutions for poultry litter"** (Leroux, 2014), showing that one of the main reasons AD subsidies were introduced was to facilitate the expansion of intensive livestock farming.

However, as DAERA itself acknowledges, "anaerobic digestion does not address the fundamental issue of excess nutrients in the manure", which are retained in the resultant digestate, meaning it has to be land spread carefully (DAERA, 2012, p. 19). Despite this, **in 2015, Moy Park was granted a licence by DAERA for its contracted farmers to produce 134,000 tonnes of chicken litter per year. Because the majority of this was sent to anaerobic digesters, it was exempted from detailed scrutiny of its impact on sensitive habitats** (SourceMaterial, 2018).

Disposing of poultry waste would have cost up to £90 a tonne (Northern Ireland Assembly, 2011) – but with heavily subsidised AD plants, Moy Park now collects waste from its contracted farmers and sells it to the digester operator (SourceMaterial, 2018). Moy Park will not disclose the price as it is "commercially sensitive", and does not even tell its own contracted farmers (SourceMaterial, 2018). However, assuming at least the £90 per tonne savings, this would amount to a **saving of approximately £12 million per year for the 134,000 tonnes of chicken litter Moy Park contract farms are licensed to produce annually**. **The demand of AD plants for a consistent large supply of slurry and manure, and paying a price for this, means that pig and poultry farms in Northern Ireland may be generating an income from excrement, creating perverse incentives for livestock farm expansion.**[42]

Northern Ireland has a history of getting renewable energy subsidies wrong – the so-called 'cash for ash' scandal rocked the government. Businesses were given RHI subsidies as incentives for them to transfer to renewable heating sources like wood pellets. However, these subsidies were often set at levels higher than the cost of the fuel, such that claimants could earn more cash the more fuel they burned, leaving the scheme open to considerable abuse. There were no clear limits on overall subsidies, so the scheme ballooned out of control, with overspend estimated at £490 million (Macauley, 2017). Moy Park's poultry farms were the biggest recipients, accounting for about half of projected 20-year scheme cost of £1.12 billion (Macauley, 2020). The scheme is especially ironic because burning wood for energy has recently been found, in most cases, to be worse than coal in terms of emissions (RSPB, FOE and Greenpeace, 2012).

Consequently, there are questions about the potential of AD subsidies to cause similar perverse incentives. Friends of the Earth Northern Ireland estimates that the 69 AD plants currently operational in Northern Ireland will each receive around £900,000 per year over 21 years, totalling over £1.3 billion (FOE NI, 2018).[43] SourceMaterial puts the estimate closer to £830 million (SourceMaterial, 2018) – but there is little doubt that the subsidies are considerable. The Northern Ireland Audit Office has already launched an **investigation into alleged overpayments** (a 500 Kw capacity plant can collect up to £500,000 a year) **and whether AD sites are being properly assessed for their environmental impact** (Archer, 2019). Friends of the Earth Northern Ireland characterises the situation as "RHI on steroids" (Bain, 2018).

---

41 In France, a similar situation has been documented, with one farmer recalling that the agricultural industry used to pay up to €90 per tonne to have such waste disposed of, whereas farmers now sell their waste for up to €20 per tonne (Lallouët-Geffroy, 2019).

42 This is based on a calculation that 179 AD plant applications had been approved in 2018, with 69 already in operation which each receive roughly £900,000 per year (apparently based on Ofgem figures) and will continue to do so for 21 years. As subsidies are not open to new plants, but are paid for 21 years to existing plants, the calculation is for 69 plants x £900,000 x 21 years.

Credit: Nordorden

The Northern Ireland example shows the very real risk that AD subsidies, set too high and targeted in the wrong way, can incentivise the growth of the very polluting sector whose effects they are meant to be mitigating – livestock. **Subsidies given in Northern Ireland were not significantly higher than subsidies in the rest of the UK in the early 2010s[43]. Although these subsidies have since declined, the UK AD industry has been lobbying for subsidies to be raised back to "2013–15 rates" and for the higher rate of subsidies given to small-scale AD to be extended to larger AD plants (ADBA, 2020a, p. 48). This creates a high risk that what happened in Northern Ireland could occurr in the rest of the UK too.** Governments around the world, including the UK, need to ensure that subsidies to AD are not making livestock farms more economically viable, and thus more likely to be built.

Due to the volume of manure and slurry required to supply AD plants and economies of scale, AD appears to be most viable for waste management at large intensive livestock farms. ADBA says that AD is especially suited to treating slurries and manures when "livestock are housed" or in "intensive livestock buildings" (ADBA, 2020a, p. 17). In the US, markets for biogas from

43 In Northern Ireland, subsidies for AD plants smaller than 500 kW were between 17–20 p/kWh, and subsidies to plants between 500 kW and 5 MW in size were about 13–15 p/kWh between 2013–17. The ADBA is proposing that AD subsidies be returned to levels between 7.9–17.5 pence per kWh (ADBA, 2020a, p. 48), and that the more generous subsidies offered to smaller AD plants be extended to larger AD plants, so in practice this would mean more uniform subsidy rates of about 15p/kWh. See Appendix 2 for more information.

AD "may have the perverse effect of intensifying herd consolidation and lagoon-manure management" because the subsidies are primarily paid to large-scale dairies and the high initial capital costs of AD plants create an incentive to pay off these costs faster by increasing the supply of manure to the digester (Mulvaney, Jordan and Martinez, 2019, pp. 29–30). One study of AD on Idaho dairy farms found that "at least 3000 cows per farm are required for an economically viable anaerobic-digestion plant operation" (Lauer *et al.*, 2018, p. 621). In Ireland, AD of pig manure may only be cost-effective on large units of 2,000 sows or more, or if centralised treatment plants are developed, with increased subsidies for electricity produced (Teagasc, 2011, p. 64). Thus, unless smaller farms are given even higher subsidies, there is a risk that AD subsidies may favour large-scale intensive farms, which often have a higher environmental footprint than smaller-scale agro-ecological farming, where AD may be less financially viable. There has been a huge increase in large intensive livestock farms in the UK in recent years (Colley and Wasley, 2020). However, the NFU argues that AD is well suited to medium-sized livestock farms (e.g. under 500 cows) if subsidies like those for RHI are preserved for smaller-scale AD (Thorpe, 2020) – though these would likely be smaller-scale AD plants producing mainly energy for the farm itself.


Credit: Lagui / Shutterstock

By 2027, it will be a legal requirement for all UK slurry pits and manure heaps to be covered, to cut ammonia emissions (Tasker, 2018). In line with the polluter pays principle, this internalises environmental externalities into the costs of business – and since large slurry pits and manure heaps are particularly common on large intensive livestock farms, it provides an important disincentive for environmentally destructive forms of farming. However, the AD industry has proposed that grants be provided by the government to farms so that they can draw financial income from the gas produced from these slurry stores through AD (ADBA, 2020a, p. vi). This risks ensuring that intensive farming is more financially viable – again perpetuating a polluting industry.

Finally, there seem to be cases where large livestock farms obtain planning permission to build their sites because they promise to build an AD plant too, in cases where their environmental impacts would otherwise mean planning permission would not be granted.

CASE STUDY 4: BROADLEY COPSE FARM

Broadley Copse Farm in West Sussex applied for planning permission to significantly expand its pig operation to finish 50,000 bacon pigs a year. However, to meet Environment Agency permit requirements, it first had to demonstrate how it would reduce potential agricultural odour from the 25,000 tonnes of pig manure which would be generated by the finishers each year (70 tonnes per day). **An AD company called Farm Renewables was brought in with the explicit aim of dealing with "odour control" and "simply what to do with [the manure] once it was removed from the sheds" – which enabled the farm to gain its permit and was "key to getting the project up and running"** (Pig World, 2019). Now that this AD plant is running, in order to pay off the £10 million it cost to build, **it must be supplied with 70 tonnes of pig manure per day, along with straw and some 20 tonnes of maize** (Pig World, 2019) – **locking in demand for the huge volumes of manure and crops for decades**.

Similar concerns have been raised that many dairies in California apply for an expansion in herd size and an AD plant at a similar time (Mulvaney, Jordan and Martinez, 2019, p. 30). In the Montauban-de-Bretagne region of France, planning permission for a livestock facility with capacity for 144,000 chickens was requested immediately after an AD plant with 1.2 MW capacity was opened nearby (Lallouët-Geffroy, 2019).

AD has been used by the UK livestock industry to argue against any dietary shifts to reduce meat consumption. The NFU has listed “Anaerobic digestion to convert animal manures, crops and crop by-products into renewable energy” as a key part of its strategy for the UK agriculture sector to reach net zero by 2040 (NFU, 2019, p. 7). In this strategy, the NFU only pledges to actively reduce its emissions by 25% while relying on BECCS for the bulk of its emissions reductions (for more info on BECCS, see Box 3). The strategy combines only slight mitigation of livestock emissions through AD with BECCS, which is untested at the scales required. This provides an excuse not to make the substantial shifts needed from agriculture in the form of reduced UK meat and dairy production and consumption, which is nowhere mentioned in the NFU strategy. Indeed, **the NFU actively opposes any reduction in UK livestock production** (NFU, 2018). **By partially papering over the deeper problem of livestock’s substantial land use and emissions, AD may be used as a greenwash tool to slow more fundamental change.**

The AD industry says that it only wants to treat “unavoidable organic wastes” (ADBA, 2020a, p. 1), but **manure and slurry are entirely avoidable – by reducing the scale of livestock production**. ADBA proposes a hierarchy for dealing with slurries and manures similar to the food waste hierarchy, enforced by regulation (ADBA, 2020a, p. vi). Prevention of slurries being produced in the first place needs to be top of this hierarchy, through a just transition to plant-based alternatives to meat and dairy.

8. CONCLUSION AND RECOMMENDATIONS

Credit: LianeM

AD does have a limited role in a transition to a sustainable future and combating climate change. However, this report shows the need for caution in assuming that AD is always the best option – and to carefully consider what the sustainable niche for AD is, to avoid displacing resources from more environmental alternatives.

It is clear that only the highest ambition will save us from the climate crisis. Especially fast and deep cuts in emissions are required in rich countries if climate equity is to be achieved (Civil Society Review, 2018; Climate Equity Reference, 2019; Jackson, 2019). To avoid disaster, we need to imagine the most ambitious path we can to a better future and throw everything we have at making this a reality, using the best available evidence as our guide. Where AD is not the optimal solution, we do not have the luxury of settling for second best. On the basis of our findings in this report, we therefore make the following recommendations to policymakers:

ELECTRICITY

AD is a less efficient means of producing electricity than solar, wind and tidal energy. Feedback therefore **recommends that renewable electricity subsidies are not given to AD**, and support is **instead directed to rapidly upscaling more efficient modes of production like wind and solar, plus energy storage solutions like batteries**. For instance, AD should be excluded from CfD subsidies – but onshore wind and solar should be included, with levels of subsidy support increased for these technologies.

GAS

There **may be some small role for AD in UK biomethane generation**, particularly if it is assumed that gas will play a strong role in UK future energy needs. However, it **is necessary to consider carefully which is more economical and sustainable – locking in subsidies and infrastructure for biomethane for decades to come and investing significant upfront costs in AD plants, or investing in faster and more comprehensive electrification of the UK heating**

and transport sectors. Actions such as building greater infrastructure for electric cars and converting heating systems to be run on electricity (such as through heat pumps) may be more prudent long-term investments than investing in AD plants. For instance, there has been encouraging research into how even heavy freight vehicles could be electrified by the 2030s (Ainalis, Thorne and Cebon, 2020) – one of the sectors the AD industry has been keen to portray as difficult to electrify. **We hope to see further comparative research being conducted into the relative economics and sustainability of these approaches.**

However, even if biomethane from AD does form an important part of our future energy mix, we need to be careful not to incentivise forms of AD which rely on unsustainable feedstocks – we turn to this subject in the sections that follow.

CROPS

The most dominant types of crops currently sent to AD are highly unsustainable – particularly maize and grass. Therefore, policy measures should be taken to disincentivise these crops being used for AD – including **removing subsidies for growing maize and grass as energy crops, and removing RHI subsidies for AD facilities that primarily use crops**. There may be other candidates in future for crops to be used in AD, but rigorous research needs to be completed to determine the sustainability and economic viability of these feedstocks, as these are currently highly uncertain.

FOOD WASTE

Governments must ensure that funding for food waste prevention is their top priority – that is, preventing wasted food from being produced in the first place, or ensuring food is used for human consumption. This is, by a considerable margin, the most environmental destination for food. Where this is not possible, **the next priority should be sending food to animal feed**. Fiscal policies, like subsidies, taxes and penalties, should be structured to ensure that it makes better economic sense to prevent food waste or send surplus food to animal feed in preference to AD, in line with the food use hierarchy. **Graded tax penalties should be applied to sending food to lower stages of the food use hierarchy – most importantly, by increasing taxes on landfill and incineration – with the money raised invested in research and action on food waste prevention**. This will incentivise AD as a last resort, enabling AD plants to charge higher gate fees, so they are more economically viable, without creating perverse incentives to divert food down the food waste hierarchy as high subsidies could do. Regulations should be introduced to go beyond the pace of change set by voluntary agreements and achieve 50% reductions of all food waste from farm to fork by 2030, against 2015 baselines. Where business practices drive food waste with upstream suppliers and downstream consumers, it is important that costs are internalised in the business that is the main driver of waste, through penalties and other means.

Credit: Chris King

MANURES AND SLURRIES

AD is environmentally beneficial in mitigating the emissions from livestock manures and slurries, but this needs to be viewed in a context in which the priority for reducing agricultural emissions should be reducing meat production and consumption through a transition to plant-based proteins. **This will inevitably restrict the volumes of manure available in future**, so AD facilities should factor this in to their growth projections. A shift away from intensive industrial farming to more sustainable models of meat production may also require downscaling the size of livestock farms. Such downscaling could reduce the concentration of manures and slurries in a small geographical area, affecting the economic viability of AD plants without significant levels of subsidy. Furthermore, there is a risk of diminishing the environmental performance of AD as transport distances increase. Finally, **extreme care should be taken to ensure policies to incentivise AD do not facilitate the expansion of livestock farming** through reducing waste disposal costs or increasing the likelihood of planning permission being granted. Where subsidies are given for AD of manure feedstocks, they should be reserved for smaller-scale, more sustainable livestock farms which have been in operation for at least 10 years, and intend to own a stake in the AD plant. This support should be conditional on the farm not expanding its livestock production. These conditions help reduce the incentives AD might provide for livestock expansion. **Carbon, methane and ammonia emissions should be taxed (which would also disincentivise sending food waste to landfill), the 2027 ban on uncovered slurry and manure stores should be brought forward, and other measures should be taken to disincentivise the most environmentally destructive livestock farming**. **These measures will incentivise farmers to invest in AD as the alternatives are so expensive or banned, but will also make the most polluting sections of the livestock industry less financially viable – the revenue raised can help fund a just transition for farmers.** This just transition should involve government grants, subsidies and retraining programmes to create good green jobs in plant-based protein production on cropland formerly used to grow animal feed, as well as in afforestation and nature restoration on former pastureland, redefining farmers as eco-stewards of agro-ecological farming and biodiverse national parks. These schemes should be complemented with increased taxation on imported meats and animal feed, to ensure UK production is not simply replaced by imports.

BIBLIOGRAPHY

Adams, P. W. R. and McManus, M. C. (2019) 'Characterisation and variability of greenhouse gas emissions from biomethane production via anaerobic digestion of maize', *Journal of Cleaner Production*, 218, pp. 529–542. doi: 10.1016/j.jclepro.2018.12.232.

ADBA (2012) *Position Paper: Anaerobic Digestion and Nutrients*. Anaerobic Digestion & Biogas Association. Available at: http://adbioresources.org/wp-content/uploads/2012/09/Nutrients-WEB.pdf (Accessed: 1 October 2019).

ADBA (2018) *Response to Committee to Committee on Climate Change Call for Evidence on Bioenergy*. Anaerobic Digestion & Biogas Association. Available at: https://www.theccc.org.uk/wp-content/uploads/2018/12/Biomass-response-to-Call-for-Evidence-ADBA.pdf (Accessed: 22 October 2019).

ADBA (2019a) *AD & Bioresources News Issue 45 Autumn 2019*. ADBA. Available at: https://ebnet.ac.uk/wp-content/uploads/sites/343/2020/03/adba-48ppa4_2019-09_digital-p26-30-and-42-43.pdf (Accessed: 12 August 2020).

ADBA (2019b) *ADBA National Conference 2019*, *ADBA National Conference 2019*. Available at: http://adbioresources.org/events/adba-national-conference/ (Accessed: 14 January 2020).

ADBA (2019c) *ADBA PRESS RELEASE – COP26 in the UK – a unique opportunity to put the UK biogas industry on the map | News*, *Anaerobic Digestion & Bioresources Association*. Available at: http://adbioresources.org/news/adba-press-release-cop26-in-the-uk-a-unique-opportunity-to-put-the-uk-bioga (Accessed: 12 February 2020).

ADBA (2019d) *PRESS RELEASE: AD industry calls for low-carbon CfD scheme to support small-scale renewables | News*, *Anaerobic Digestion & Bioresources Association*. Available at: http://adbioresources.org/news/press-release-ad-industry-calls-for-low-carbon-cfd-scheme-to-support-small (Accessed: 17 February 2020).

ADBA (2019e) *The World Biogas Summit 2019 | Events*, *ADBA | Anaerobic Digestion & Bioresources Association*. Available at: http://adbioresources.org/events/the-world-biogas-summit-2019 (Accessed: 12 February 2020).

ADBA (2020a) *Biomethane: Pathway to 2030*. Anaerobic Digestion & Biogas Association. Available at: http://adbioresources.org/docs/Biomethane_-_Pathway_to_2030_-_Full_report.pdf (Accessed: 9 July 2020).

ADBA (2020b) *Prime Minister confirms a successor to the RHI in the pipeline*, *Anaerobic Digestion & Bioresources Association*. Available at: http://adbioresources.org/news/prime-minister-confirms-a-successor-to-the-rhi-in-the-pipeline (Accessed: 17 February 2020).

AFSB (2014) *Members*, *Agri-Food Strategy Board*. Available at: https://web.archive.org/web/20140606030856/http:/www.agrifoodstrategyboard.org.uk:80/members (Accessed: 9 March 2020).

Ainalis, D. T., Thorne, C. and Cebon, D. (2020) *Decarbonising the UK's Long-Haul Road Freight at Minimum Economic Cost*. The Centre for Sustainable Road Freight. Available at: http://www.csrf.ac.uk/wp-content/uploads/2020/07/SRF-WP-UKEMS-v2.pdf (Accessed: 27 July 2020).

Alberici, S., Toop, G. and Critchley, S. (2018) *Bioenergy heat pathways to 2050 – rapid evidence assessment: Summary report*. Ecofys for Department for Business, Energy & Industrial Strategy (BEIS), p. 48. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760328/BE1_D7_Biomass_Heat_REA_FINAL_Summary_Report_for_publication.pdf (Accessed: 20 February 2020).

Aleksandrowicz, L., Green, R., Joy, E. J. M., Smith, P. and Haines, A. (2016) 'The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review', *PLOS ONE*, 11(11), p. e0165797. doi: 10.1371/journal.pone.0165797.

Ambrose, J. (2020) 'UK government lifts block on new onshore windfarm subsidies', *The Guardian*, 2 March. Available at: https://www.theguardian.com/business/2020/mar/02/uk-government-lifts-block-on-new-onshore-windfarm-subsidies (Accessed: 12 March 2020).

Ancala Partners LLP (2019) *Ancala Partners LLP: Annual report and consolidated financial statements*. Companies House.

Archer, B. (2019) *Audit Office investigating lucrative anaerobic digester plant subsidies*, *The Irish News*. Available at: http://www.irishnews.com/news/northernirelandnews/2019/07/29/news/audit-office-investigating-lucrative-anaerobic-digester-plant-subsidies-1672187/ (Accessed: 13 February 2020).

Assured Energy LLP (2018) *Assured Energy LLP: Annual Report and Financial Statements for the year ended 31 March 2018*. Companies House.

Bahrs, E. and Angenendt, E. (2019) 'Status quo and perspectives of biogas production for energy and material utilization', *GCB Bioenergy*, 11(1), pp. 9–20. doi: 10.1111/gcbb.12548.

Bain, M. (2018) 'Northern Ireland agri-firms could make billions milking scheme branded "RHI on steroids": claim', *Belfast Telegraph*, 15 November. Available at: https://www.belfasttelegraph.co.uk/business/agri/northern-ireland-agri-firms-could-make-billions-milking-scheme-branded-rhi-on-steroids-claim-37529890.html (Accessed: 13 February 2020).

Bajželj, B. (2014a) 'Importance of food-demand management for climate mitigation.', *Nature Climate Change*, 4, pp. 924–929. doi: https://doi.org/10.1038/nclimate2353.

Bajželj, B. (2014b) 'Importance of food-demand management for climate mitigation.', *Nature Climate Change*, 4, pp. 924–929.

Bastin, J.-F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D., Zohner, C. M. and Crowther, T. W. (2019) 'The global tree restoration potential', *Science*, 365(6448), pp. 76–79. doi: 10.1126/science.aax0848.

BEIS (2017) *Electricity Market Reform: Contracts for Difference*, *GOV.UK*. Available at: https://www.gov.uk/government/collections/electricity-market-reform-contracts-for-difference (Accessed: 18 February 2020).

BEIS (2019a) *Digest of UK Energy Statistics 2019*. Department for Business, Energy and Industrial Strategy. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/820277/DUKES_2019_Press_Notice_GOV.UK.pdf (Accessed: 12 March 2020).

BEIS (2019b) *Digest of UK Energy Statistics (DUKES): renewable sources of energy – DUKES Chapter 6: Renewable sources of energy*. Department for Business, Energy and Industrial Strategy. Available at: https://www.gov.uk/government/statistics/renewable-sources-of-energy-chapter-6-digest-of-united-kingdom-energy-statistics-dukes (Accessed: 18 February 2020).

BEIS (2019c) *Energy Consumption in the UK (ECUK) 1970 to 2018*. London.

BEIS (2020) *2018 UK Greenhouse Gas Emissions, Final figures*. Department for Business, Energy and Industrial Strategy, p. 41. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/862887/2018_Final_greenhouse_gas_emissions_statistical_release.pdf (Accessed: 26 March 2020).

Benson, I. (2019a) *ADBA calls on new government to support AD industry*, *Resource Magazine*. Available at: https://resource.co/article/adba-calls-new-government-support-ad-industry (Accessed: 17 December 2019).

Benson, I. (2019b) *World Biogas Association makes emissions reduction declaration at COP25*, *Resource Magazine*. Available at: https://resource.co/article/world-biogas-association-makes-emissions-reduction-declaration-cop25 (Accessed: 17 December 2019).

Biogas Info (2019) *Digestate*, *Anaerobic Digestion*. Available at: http://www.biogas-info.co.uk/about/digestate/ (Accessed: 1 October 2019).

Biogas Info (2020) 'Feedstocks | Anaerobic Digestion', *Biogas Info*. Available at: http://www.biogas-info.co.uk/about/feedstocks/ (Accessed: 5 March 2020).

Biogen (2019) *Where We Operate*, *Biogen*. Available at: http://www.biogen.co.uk/Where-we-operate (Accessed: 30 September 2019).

Booth, R. and Pegg, D. (2018) 'Jersey Finance paid for IEA report rubbishing "hotbeds of tax evasion" claims', *The Guardian*, 31 July. Available at: https://www.theguardian.com/uk-news/2018/jul/31/jersey-finance-paid-iea-to-trash-hotbeds-of-tax-evasion-claims (Accessed: 26 September 2019).

Bowman, M. (2020) 'Feedback responds to new food waste figures', *Feedback*, 24 January. Available at: https://feedbackglobal.org/feedbacks-responds-to-new-food-waste-figures/ (Accessed: 12 May 2020).

Boysen, L. R., Lucht, W., Gerten, D., Heck, V., Lenton, T. M. and Schellnhuber, H. J. (2017) 'The limits to global-warming mitigation by terrestrial carbon removal', *Earth's Future*, 5(5), pp. 463–474.

British Gas (2020) *Smart Export Guarantee*, *British Gas*. Available at: https://www.britishgas.co.uk/business/help-and-support/billing-and-payments/smart-export-guarantee (Accessed: 17 February 2020).

Bulb (2020) *Getting paid for exported electricity*, *Bulb*. Available at: http://help.bulb.co.uk/hc/en-us/articles/360038160851-Getting-paid-for-exported-electricity (Accessed: 17 February 2020).

CEH and Rothamsted Research (2019) *Quantifying the impact of future land use scenarios to 2050 and beyond – Final Report*. Committee on Climate Change. Available at: https://www.theccc.org.uk/wp-content/uploads/2018/11/Quantifying-the-impact-of-future-land-use-scenarios-to-2050-and-beyond-Full-Report.pdf (Accessed: 13 May 2019).

Civil Society Review (2018) *After Paris: Inequality, Fair Shares, and the Climate Emergency – A Civil Society Science and Equity-Based Assessment of the NDCs*. Civil Society Review. Available at: http://civilsocietyreview.org/files/COP24_CSO_Equity_Review_Report.pdf (Accessed: 31 August 2019).

Climate Equity Reference (2019) *Climate Equity Reference Calculator*, *Climate Equity Reference Calculator*. Available at: https://calculator.climateequityreference.org/ (Accessed: 30 August 2019).

Colbert, E. (2017) *Causes of food waste in international supply chains*. Feedback. Available at: https://feedbackglobal.org/wp-content/uploads/2017/05/Causes-of-food-waste-in-international-supply-chains_Feedback.pdf.

Colley, C. and Wasley, A. (2020) 'Industrial-sized pig and chicken farming continuing to rise in UK', *The Guardian*, 7 April. Available at: https://www.theguardian.com/environment/2020/apr/07/industrial-sized-pig-and-chicken-farming-continuing-to-rise-in-uk (Accessed: 8 April 2020).

Committee for Enterprise, Trade and Investment (2014) *OFFICIAL REPORT (Hansard) – Going for Growth: Agri-Food Strategy Board and Department of Enterprise, Trade and Investment*. Committee for Enterprise, Trade and Investment. Available at: http://www.niassembly.gov.uk/globalassets/documents/official-reports/eti/2014-2015/141014_goingforgrowthafsbdeti.pdf (Accessed: 9 March 2020).

Committee on Climate Change (2018) *Land use: Reducing emissions and preparing for climate change*. Committee on Climate Change. Available at: https://www.theccc.org.uk/wp-content/uploads/2018/11/Land-use-Reducing-emissions-and-preparing-for-climate-change-CCC-2018.pdf (Accessed: 4 November 2019).

Committee on Climate Change (2019a) *Net Zero: Technical report*. Committee on Climate Change. Available at: https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-Technical-report-CCC.pdf (Accessed: 13 May 2019).

Committee on Climate Change (2019b) *Net Zero: Technical report*. Committee on Climate Change. Available at: https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-Technical-report-CCC.pdf (Accessed: 13 May 2019).

Committee on Climate Change (2019c) *Net Zero: The UK's contribution to stopping global warming*. Committee on Climate Change. Available at: https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf (Accessed: 13 May 2019).

Committee on Climate Change (2020a) *Land Use: Policies for a Net Zero UK*. Committee on Climate Change. Available at: https://www.theccc.org.uk/wp-content/uploads/2020/01/Land-use-Policies-for-a-Net-Zero-UK.pdf (Accessed: 19 February 2020).

Committee on Climate Change (2020b) *Reducing UK emissions: 2020 Progress Report to Parliament*. London: Committee on Climate Change. Available at: https://www.theccc.org.uk/publication/reducing-uk-emissions-2020-progress-report-to-parliament/ (Accessed: 9 July 2020).

DAC Beachcroft (2019) *UK anaerobic digestion readies for revival in 2019*. DAC Beachcroft. Available at: https://www.dacbeachcroft.com/media/1351777/uk-anaerobic-digestion-readies-for-revival-in-2019.pdf (Accessed: 30 September 2019).

DAERA (2012) *Review of Alternative Technologies to Fluidised Bed Conbustion for Poultry Litter Utilisation/Disposal*. DAERA, p. 36. Available at: https://www.daera-ni.gov.uk/sites/default/files/publications/dard/review-of-alternative-technologies-for-poultry-litter-final-jan-2012.pdf (Accessed: 3 October 2020).

DAERA (2013a) *Going for Growth: A strategic action plan in support of the Northern Ireland Agri-Food Industry*. Northern Ireland: Agri-Food Strategy Board, DAERA. Available at: https://www.daera-ni.gov.uk/sites/default/files/publications/dard/going-for-growth.pdf (Accessed: 13 February 2020).

DAERA (2013b) *The Agricultural Census in Northern Ireland: Results for June 2013*. Department of Agriculture and Rural Development. Available at: https://www.daera-ni.gov.uk/sites/default/files/publications/dard/agricultural-census-in-ni-2013-1.pdf (Accessed: 7 April 2020).

DAERA (2020) *The Agricultural Census in Northern Ireland: Results for June 2019*. Department of Agriculture, Environment and Rural Affairs. Available at: https://www.daera-ni.gov.uk/sites/default/files/publications/daera/Agricultural%20Census%202019%20Rev%201.pdf (Accessed: 7 April 2020).

Davidson, G. (2019) *Anaerobic digestion sector appeals for more political support*, *The Scottish Farmer*. Available at: https://www.thescottishfarmer.co.uk/diversification/18084677.anaerobic-digestion-sector-appeals-political-support/ (Accessed: 17 December 2019).

Defra (2014) *Review of Landfill Methane Emissions Modelling – WR1908*. Department for Environment, Food and Rural Affairs. Available at: http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=18923 (Accessed: 8 April 2020).

Defra (2015) *Anaerobic Digestion Strategy and Action Plan: Annual Report 2014*. Department for Environment, Food and Rural Affairs, p. 24. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/406928/pb14019-anaerobic-digestion-annual-report-2013-14.pdf (Accessed: 30 September 2019).

Defra (2019a) *Agriculture in the United Kingdom 2018*. Department for Environment, Food and Rural Affairs. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/815303/AUK_2018_09jul19.pdf (Accessed: 5 September 2019).

Defra (2019b) *Crops Grown For Bioenergy in the UK: 2017*. Department for Environment, Food and Rural Affairs. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/775243/nonfood-statsnotice2017-31jan19i.pdf (Accessed: 30 July 2019).

Defra (2019c) *Crops Grown For Bioenergy in the UK: 2018*. Department for Environment, Food and Rural Affairs. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/856695/nonfood-statsnotice2018-08jan20.pdf (Accessed: 12 March 2020).

Defra and DECC (2011) *Anaerobic Digestion Strategy and Action Plan: A commitment to increasing energy from waste through Anaerobic Digestion*. London: Department for Environment, Food and Rural Affairs and Department of Energy and Climate Change, p. 56. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69400/anaerobic-digestion-strat-action-plan.pdf (Accessed: 15 January 2020).

Department for Transport (2020) *Renewable Transport Fuel Obligation*, *GOV.UK*. Available at: https://www.gov.uk/guidance/renewable-transport-fuels-obligation (Accessed: 18 February 2020).

Department of Energy and Climate Change (2014) *Contract for Difference: Final Allocation Framework for the October 2014 Allocation Round*. London: Department of Energy and Climate Change. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/404405/Contract_for_Difference_Final_Allocation_Framework_for_the_October_2014_Allocation_Round.pdf (Accessed: 17 February 2020).

Dick, H. and Scholes, P. (2019a) *Comparing the costs of alternative waste treatment options for commercial waste*. Anthesis for WRAP, p. 24. Available at: https://www.wrap.org.uk/sites/files/wrap/WRAP%20Commercial%20Gate%20Fees%202019.pdf (Accessed: 16 March 2020).

Dick, H. and Scholes, P. (2019b) *Gate Fees 2018/19 Report: Comparing the costs of alternative waste treatment options*. WRAP and Anthesis, p. 72. Available at: https://www.wrap.org.uk/sites/files/wrap/WRAP%20gate%20fees%20report%202019.pdf (Accessed: 14 February 2020).

Edwards, J., Othman, M., Crossin, E. and Burn, S. (2017) 'Anaerobic co-digestion of municipal food waste and sewage sludge: A comparative life cycle assessment in the context of a waste service provision', *Bioresource Technology*, 223, pp. 237–249. doi: 10.1016/j.biortech.2016.10.044.

zu Ermgassen, E. K. H. J., Phalan, B., Green, R. and Balmford, A. (2016) 'Reducing the land use of EU pork production: where there's swill, there's a way', *Food Policy*, 58, pp. 35–48. doi: 10.1016/j.foodpol.2015.11.001.

European Commission (2019) *The Commission specifies the criteria to ensure that biofuels used in the transport sector are sustainable in the context of the recast Renewable Energy Directive*, *European Commission – European Commission*. Available at: https://ec.europa.eu/info/news/commission-specifies-criteria-ensure-biofuels-used-transport-sector-are-sustainable-context-recast-renewable-energy-directive-2019-mar-13_en (Accessed: 20 February 2020).

Eurostat (2020) *Glossary: Types of manure application*, *Eurostat: Statistics Explained*. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Type_of_manure_application (Accessed: 8 April 2020).

Evangelisti, S., Lettieri, P., Borello, D. and Clift, R. (2014) 'Life cycle assessment of energy from waste via anaerobic digestion: a UK case study', *Waste Management (New York, N.Y.)*, 34(1), pp. 226–237. doi: 10.1016/j.wasman.2013.09.013.

FareShare (2017) *Help us #feedpeoplefirst: sign the petition*, *FareShare*. Available at: https://fareshare.org.uk/get-involved/feedpeoplefirst/ (Accessed: 20 February 2020).

Farm Carbon Toolkit (2019) *Fertiliser production*, *Farm Carbon Cutting Toolkit*. Available at: https://www.farmcarbontoolkit.org.uk/toolkit/fertiliser-production (Accessed: 21 February 2020).

Farnworth, G. and Melchett, P. (2015) *Runaway Maize: Subsidised soil destruction*. Bristol: Soil Association. Available at: https://www.soilassociation.org/media/4671/runaway-maize-june-2015.pdf (Accessed: 23 July 2019).

Feedback (2020) *Big Livestock Versus the Planet*. London: Feedback. Available at: https://feedbackglobal.org/wp-content/uploads/2020/04/Feedback-Big-Livestock-versus-the-Planet-Final-April-2020.pdf (Accessed: 27 July 2020).

Fitzgerald, L. M., Braunger, I. and Brauers, H. (2019) *Destabilisation of Sustainable Energy Transformations: Analysing Natural Gas Lock-in in the case of Germany*. 106. Brighton: IDS. Available at: https://www.ids.ac.uk/publications/destabilisation-of-sustainable-energy-transformations-analysing-natural-gas-lock-in-in-the-case-of-germany/ (Accessed: 14 January 2020).

FOE NI (2018) *Fighting the pig slurry in Northern Ireland*, *Friends of the Earth Northern Ireland*. Available at: https://friendsoftheearth.uk/northern-ireland/fighting-pig-slurry-northern-ireland (Accessed: 13 February 2020).

Foresight Group (2016) *Foresight picks up Best IHT Portfolio Service at the 2016/17 Tax Efficiency Awards*, *Foresight Group*. Available at: https://www.foresightgroup.eu/news/foresight-picks-up-best-iht-portfolio-service-at-the-2016-17-tax-efficiency-awards/ (Accessed: 30 September 2019).

Replace with Foresight Group (2020) *FP FORESIGHT UK INFRASTRUCTURE INCOME FUND* Factsheet 31 July 2020, Foresight Group. Available at: https://www.foresightgroup.eu/media/osidc5yv/fiif-factsheet-july-2020.pdf

Foresight Group (2019) *Bioenergy Generation Infrastructure Investments | Foresight Group*, *Foresight Group*. Available at: https://www.foresightgroup.eu/infrastructure/renewable-energy-generation/bioenergy/ (Accessed: 30 September 2019).

Foresight Group (2019) *Foresight Group: An Introduction – Corporate Profile Autumn 2019*, London: Foresight Group. Available at: https://www.foresightgroup.eu/media/mwaponyu/foresight-group-corporate-profile-autumn-2019.pdf

Fusi, A., Bacenetti, J., Fiala, M. and Azapagic, A. (2016) 'Life Cycle Environmental Impacts of Electricity from Biogas Produced by Anaerobic Digestion', *Frontiers in Bioengineering and Biotechnology*, 4. doi: 10.3389/fbioe.2016.00026.

Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., Jackson, R. B., Jones, C. D., Kraxner, F., Nakicenovic, N., Le Quéré, C., Raupach, M. R., Sharifi, A., Smith, P. and Yamagata, Y. (2014) 'Betting on negative emissions', *Nature Climate Change*. Nature Publishing Group, 4(10), pp. 850–853. doi: 10.1038/nclimate2392.

GCP Infrastructure Investments Limited (2015) *Monthly factsheet: 30 October 2015*. GCP Infrastructure Investments Limited. Available at: https://www.graviscapital.com/uploads/fund-documents/gcp-infra/GCPIIL_Fact-Sheet-Oct-15_4.pdf (Accessed: 26 September 2019).

GCP Infrastructure Investments Limited (2019) *GCP INFRASTRUCTURE INVESTMENTS LIMITED Annual report and financial statements 2018*. Available at: https://www.graviscapital.com/uploads/fund-documents/gcp-infra/web03a_GCPII_AR18.pdf (Accessed: 26 September 2019).

Gerber, P. J. and FAO (eds) (2013) *Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities*. Rome: Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/3/i3437e/i3437e.pdf (Accessed: 13 February 2020).

Godfray, H. C. J., Aveyard, P., Garnett, T., Hall, J. W., Key, T. J., Lorimer, J., Pierrehumbert, R. T., Scarborough, P., Springmann, M. and Jebb, S. A. (2018) 'Meat consumption, health, and the environment', *Science*, 361(6399), p. eaam5324.

Hanson, C. (2017) *Guidance on Interpreting Sustainable Development Goal Target 12.3*. Champions 12.3. Available at: https://champs123blog.files.wordpress.com/2017/10/champions-12-3-guidance-on-interpreting-sdg-target-12-3.pdf (Accessed: 3 April 2018).

Harwatt, H. and Hayek, M. N. (2019) *Eating Away at Climate Change with Negative Emissions: Repurposing UK agricultural land to meet climate goals*. Harvard Law School. Available at: https://growgreenconference.com/sites/default/files/uploads/Eating%20Away%20at%20Climate%20Change%20with%20Negative%20Emissions.pdf (Accessed: 4 July 2019).

Herman, M.-O., Mayrhofer, J. and Mayrhofer, J. (2016) *Burning Land, Burning the Climate: The biofuel industry's capture of EU bioenergy policy*. Oxfam, p. 44.

Herrmann, A. (2013) 'Biogas Production from Maize: Current State, Challenges and Prospects. 2. Agronomic and Environmental Aspects', *BioEnergy Research*, 6(1), pp. 372–387. doi: 10.1007/s12155-012-9227-x.

Hijazi, O., Munro, S., Zerhusen, B. and Effenberger, M. (2016) 'Review of life cycle assessment for biogas production in Europe', *Renewable and Sustainable Energy Reviews*, 54, pp. 1291–1300. doi: 10.1016/j.rser.2015.10.013.

HM Government (2018) *Our waste, our resources: a strategy for England*. Defra. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/765914/resources-waste-strategy-dec-2018.pdf (Accessed: 5 January 2019).

House of Lords EU Committee (2013) *Counting the Cost of Food Waste: EU Food Waste Prevention*. HL Paper 154, 10th Report of Session 2013–14. London: The Stationery Office, p. 78. Available at: https://www.parliament.uk/documents/lords-committees/eu-sub-com-d/food-waste-prevention/154.pdf (Accessed: 4 March 2018).

Ingrams, S. (2019) *Smart Export Guarantee explained*, *Which?* Available at: https://www.which.co.uk/reviews/solar-panels/article/smart-export-guarantee-explained (Accessed: 15 February 2020).

Jackson, T. (2019) *Zero Carbon Sooner – The case for an early zero carbon target for the UK*. CUSP Working Paper No 18. Guildford: Centre for the Understanding of Sustainable Prosperity, University of Surrey, p. 12. Available at: https://www.cusp.ac.uk/wp-content/uploads/WP18%E2%80%94Zero-carbon-sooner.pdf (Accessed: 30 July 2019).

JLEN (2019) *Anaerobic digestion*, *JLEN – John Laing Environmental Assets Group*. Available at: https://jlen.com/portfolio/anaerobic-digestion/ (Accessed: 1 October 2019).

Kampman, B., Leguijt, C., Scholten, T., Tallat-Kelpsaite, J., Brückmann, R., Maroulis, G., Lesschen, J. P., Meesters, K., Sikirica, N. and Elbersen, B. (2016) *An assessment of the potential of biogas from digestion in the EU beyond 2020*. CE Delft, Eclareon and Wageningen Research for the European Commission, p. 158. Available at: https://ec.europa.eu/energy/sites/ener/files/documents/ce_delft_3g84_biogas_beyond_2020_final_report.pdf (Accessed: 22 October 2019).

Khan, S. (2018) *Government announces £15 million project to cut food waste*, *The Independent*. Available at: https://www.independent.co.uk/news/uk/politics/michael-gove-cut-food-waste-help-a-hungry-child-the-felix-project-a8565266.html (Accessed: 28 June 2019).

Kim, B., Neff, R., Santo, R. and Vigorito, J. (2015) 'The Importance of Reducing Animal Product Consumption and Wasted Food in Mitigating Catastrophic Climate Change', p. 8.

Köhler, F. E. (1897) 'Köhler's Medizinal-Pflanzen', *Wikimedia Commons*. Available at: https://en.wikipedia.org/wiki/File:Zea_mays_-_K%C3%B6hler%E2%80%93s_Medizinal-Pflanzen-283.jpg (Accessed: 12 August 2020).

Lallouët-Geffroy, J. (2019) *La méthanisation risque d'accélérer la concentration des fermes*, *Reporterre, le quotidien de l'écologie*. Available at: https://reporterre.net/La-methanisation-risque-d-accelerer-la-concentration-des-fermes (Accessed: 8 April 2020).

Lauer, M., Hansen, J. K., Lamers, P. and Thrän, D. (2018) 'Making money from waste: The economic viability of producing biogas and biomethane in the Idaho dairy industry', *Applied Energy*, 222, pp. 621–636. doi: 10.1016/j.apenergy.2018.04.026.

Leroux, M. (2014) *Q&A for permanent secretary for before meeting with Moy Park in 2014*, *Scribd*. Available at: https://www.scribd.com/document/392987767/Q-A-for-permanent-secretary-for-before-meeting-with-Moy-Park-in-2014 (Accessed: 10 March 2020).

Luyckx, K. and Bowman, M. (2018) *Feeding Surplus Food to Pigs Safely: A win-win for farmers and the environment*. London: Feedback. Available at: https://feedbackglobal.org/wp/wp-content/uploads/2018/07/Pig-Idea-UK-policy-report.pdf (Accessed: 3 September 2018).

Luyckx, K., Bowman, M., Broeze, J., Taillard, D. and Woroniecka, K. (2019) *Technical guidelines animal feed: The safety, environmental and economic aspects of feeding treated surplus food to omnivorous livestock. REFRESH Deliverable 6.7.* Available at: https://eu-refresh.org/results.

Macauley, C. (2017) 'PSNI considering RHI fraud investigation', *BBC News*, 18 January. Available at: https://www.bbc.com/news/uk-northern-ireland-38656523 (Accessed: 13 February 2020).

Macauley, C. (2018) 'Green energy plants planning concerns', *BBC News*, 13 November. Available at: https://www.bbc.com/news/uk-northern-ireland-46178533 (Accessed: 13 February 2020).

Macauley, C. (2020) 'The key questions from the RHI inquiry', *BBC News*, 13 March. Available at: https://www.bbc.com/news/uk-northern-ireland-51755993 (Accessed: 8 April 2020).

Mackey, B., Prentice, I. C., Steffen, W., House, J. I., Lindenmayer, D., Keith, H. and Berry, S. (2013) 'Untangling the confusion around land carbon science and climate change mitigation policy', *Nature Climate Change*. Nature Publishing Group, 3(6), pp. 552–557. doi: 10.1038/nclimate1804.

Mesa-Dominguez, E., Styles, D., Zennaro, K. and Thompson, P. (2015) *Evaluating cost-effective greenhouse gas abatement by small-scale anaerobic digestion*. Renewable Energy Association and Bangor University, p. 19. Available at: https://www.researchgate.net/publication/299354211_Evaluating_cost-effective_greenhouse_gas_abatement_by_small-scale_anaerobic_digestion (Accessed: 26 September 2019).

Meyer-Aurich, A., Schattauer, A., Hellebrand, H. J., Klauss, H., Plöchl, M. and Berg, W. (2012) 'Impact of uncertainties on greenhouse gas mitigation potential of biogas production from agricultural resources', *Renewable Energy*, 37(1), pp. 277–284. doi: 10.1016/j.renene.2011.06.030.

Milner, J., Green, R., Dangour, A. D., Haines, A., Chalabi, Z., Spadaro, J., Markandya, A. and Wilkinson, P. (2015) 'Health effects of adopting low greenhouse gas emission diets in the UK', *BMJ open*, 5(4), p. e007364.

Moore, D. (2013), 'Green Investment Bank Publishes Market Report on Anaerobic Digestion', Circular Magazine, 11 June. Available at: https://www.circularonline.co.uk/news/green-investment-bank-publishes-market-report-on-anaerobic-digestion/

Moult, J. A., Allan, S. R., Hewitt, C. N. and Berners-Lee, M. (2018a) 'Greenhouse gas emissions of food waste disposal options for UK retailers', *Food Policy*, 77, pp. 50–58. doi: 10.1016/j.foodpol.2018.04.003.

Moult, J. A., Allan, S. R., Hewitt, C. N. and Berners-Lee, M. (2018b) 'Greenhouse gas emissions of food waste disposal options for UK retailers', *Food Policy*, 77, pp. 50–58. doi: 10.1016/j.foodpol.2018.04.003.

Mulvaney, D., Jordan, J. and Martinez, L. (2019) *Prepared Testimony of Dr Justin Mulvaney, Julia Jordan, and Leslie Martinez on Behalf of Sierra Club and Leadership Counsel for Justice and Accountability on the Application of Southern California Gas Company and San Diego Gas and Electric Company for Renewable Natural Gas Tariff*. Sierra Club and Leadership Counsel for Justice and Accountability. Available at: https://www.cpuc.ca.gov/uploadedFiles/CPUC_Website/Content/Utilities_and_Industries/Energy/Energy_Programs/Gas/Natural_Gas_Market/2019-10-14_Sierra%20Club%20and%20Leadership%20Counsel_Prepared%20Testimony%20of%20Mulvaney%20Jordan%20Martinez.pdf (Accessed: 18 February 2020).

Murray, J. (2018) *WRAP facing up to 25 job losses following cuts to government funding*, *http://www.businessgreen.com*. Available at: https://www.businessgreen.com/bg/news/3024593/wrap-facing-up-to-25-job-losses-following-cuts-to-government-funding (Accessed: 28 June 2019).

Neslen, A. (2012) 'EU calls time on first-generation biofuels', *www.euractiv.com*, 18 October. Available at: https://www.euractiv.com/section/climate-environment/news/eu-calls-time-on-first-generation-biofuels/ (Accessed: 20 February 2020).

NFU (2013) *NFU Briefing: Anaerobic Digestion: can we attain NFU's aspiration for 1000 on-farm plants*. National Farmers Union. Available at: https://www.nfuonline.com/assets/22388 (Accessed: 20 February 2020).

NFU (2018) *NFU response to Committee on Climate Change report*, *NFU Online*. Available at: https://www.nfuonline.com:443/news/latest-news/nfu-response-to-committee-on-climate-change-report/ (Accessed: 12 March 2020).

NFU (2019) *Achieving Net Zero: Farming's 2040 goal*. Stoneleigh, Warwickshire: National Farmers Union. Available at: https://www.nfuonline.com/nfu-online/business/regulation/achieving-net-zero-farmings-2040-goal/ (Accessed: 19 February 2020).

Nicholson, C. (2020) '"There are many benefits to growing protein crops in Scotland"', *Press and Journal*. Available at: https://www.pressandjournal.co.uk/fp/business/farming/2384686/there-are-many-benefits-to-growing-protein-crops-in-scotland/ (Accessed: 11 August 2020).

Nierynck, R. (2016) *AD subsidy available through CfD scheme*, *letsrecycle.com*. Available at: https://www.letsrecycle.com/news/latest-news/ad-subsidy-available-through-cfd-scheme/ (Accessed: 17 February 2020).

NNFCC (2019) **NEW* Anaerobic Digestion Deployment in the UK*, *NNFCC The Bioeconomy Consultants*. Available at: https://www.nnfcc.co.uk/report-anaerobic-digestion-deployment-in-the-uk (Accessed: 30 July 2019).

Northern Ireland Assembly (2011) *Weekly Answers Booklet: Friday 07 January 2011 Written Answers to Questions*, *Northern Ireland Assembly*. Information Office, Northern Ireland Assembly, info.office@niasembly.gov.uk. Available at: http://archive.niassembly.gov.uk/qanda/2007mandate/writtenans/2010/110107.htm (Accessed: 10 March 2020).

Pacetti, T., Lombardi, L. and Federici, G. (2015) 'Water–energy Nexus: a case of biogas production from energy crops evaluated by Water Footprint and Life Cycle Assessment (LCA) methods', *Journal of Cleaner Production*, 101, pp. 278–291. doi: 10.1016/j.jclepro.2015.03.084.

Palmer, R. C. and Smith, R. P. (2013) 'Soil structural degradation in SW England and its impact on surface-water runoff generation', *Soil Use and Management*, 29(4), pp. 567–575. doi: 10.1111/sum.12068.

Paolini, V., Petracchini, F., Segreto, M., Tomassetti, L., Naja, N. and Cecinato, A. (2018) 'Environmental impact of biogas: A short review of current knowledge', *Journal of Environmental Science and Health, Part A*. Taylor & Francis, 53(10), pp. 899–906. doi: 10.1080/10934529.2018.1459076.

Pig World (2019) 'Powered by pigs | Pig World', *Pig World*, 11 August. Available at: http://www.pig-world.co.uk/features/powered-by-pigs.html (Accessed: 8 April 2020).

Poore, J. and Nemecek, T. (2018) 'Reducing food's environmental impacts through producers and consumers', *Science*, 360(6392), pp. 987–992. doi: 10.1126/science.aaq0216.

Poux, X. and Aubert, P.-M. (2018) *An agroecological Europe in 2050: multifunctional agriculture for healthy eating*. IDDRI, p. 74. Available at: https://www.soilassociation.org/media/18074/iddri-study-tyfa.pdf (Accessed: 1 October 2019).

Private Equity Wire (2018) *Aurium, Equitix and Helios establish new AD venture*, *Private Equity Wire*. Available at: https://www.privateequitywire.co.uk/2018/09/04/267964/aurium-equitix-and-helios-establish-new-ad-venture (Accessed: 1 October 2019).

Purdy, S. J., Maddison, A. L., Nunn, C. P., Winters, A., Timms□Taravella, E., Jones, C. M., Clifton□Brown, J. C., Donnison, I. S. and Gallagher, J. A. (2017) 'Could Miscanthus replace maize as the preferred substrate for anaerobic digestion in the United Kingdom? Future breeding strategies', *GCB Bioenergy*, 9(6), pp. 1122–1139. doi: 10.1111/gcbb.12419.

Reece, A. (2013) *Defra cuts WRAP funding*, *Resource Magazine*. Available at: https://resource.co/article/UK/Defra_cuts_WRAP_funding-3262 (Accessed: 28 June 2019).

Resource (2017) *It all ADs up: Boosting food waste supply to anaerobic digestion*, *Resource Magazine*. Available at: https://resource.co/article/it-all-ads-boosting-food-waste-supply-anaerobic-digestion-12084 (Accessed: 30 October 2019).

Riley, J. (2017) *What can slurry-only AD plants offer dairy farmers?*, *Farmers Weekly*. Available at: https://www.fwi.co.uk/livestock/can-slurry-ad-plants-offer-dairy-farmers (Accessed: 4 March 2020).

RSPB, FOE and Greenpeace (2012) *Dirtier than Coal? Why government plans to subsidise burning trees are bad news for the planet*. RSPB, Friends of the Earth and Greenpeace. Available at: http://ww2.rspb.org.uk/Images/biomass_report_tcm9-326672.pdf (Accessed: 13 February 2020).

Salemdeeb, R., zu Ermgassen, E. K. H. J., Kim, M. H., Balmford, A. and Al-Tabbaa, and A. (2017) 'Environmental and health impacts of using food waste as animal feed: a comparative analysis of food waste management options.', *Journal of cleaner production*, 140, pp. 871–880.

Scottish Power (2020) *What is the Smart Export Guarantee (SEG)?*, *Scottish Power*. Available at: https://www.scottishpower.co.uk/energy-efficiency/smart-export-guarantee (Accessed: 17 February 2020).

Sliz-Szkliniarz, B. and Vogt, J. (2012) 'A GIS-based approach for evaluating the potential of biogas production from livestock manure and crops at a regional scale: A case study for the Kujawsko-Pomorskie Voivodeship', *Renewable and Sustainable Energy Reviews*, 16(1), pp. 752–763. doi: 10.1016/j.rser.2011.09.001.

Smetana, S., Schmitt, E. and Mathys, A. (2019) 'Sustainable use of Hermetia illucens insect biomass for feed and food: Attributional and consequential life cycle assessment', *Resources, Conservation and Recycling*, 144, pp. 285–296. doi: 10.1016/j.resconrec.2019.01.042.

Smith, C. (2019) *CfD Challenges and the Case for Onshore Wind*, *SmartestEnergy*. Available at: https://smartestenergy.com/info-hub/blog/cfd-challenges-and-the-case-for-onshore-wind/ (Accessed: 18 February 2020).

Smith, K. A. and Williams, A. G. (2016) 'Production and management of cattle manure in the UK and implications for land application practice', *Soil Use and Management*, 32(S1), pp. 73–82. doi: 10.1111/sum.12247.

SourceMaterial (2018) *Muck for Brass*, *Source Material*. Available at: https://www.source-material.org/blog/muck-for-brass (Accessed: 9 March 2020).

Styles, D., Gibbons, J., Williams, A. P., Dauber, J., Stichnothe, H., Urban, B., Chadwick, D. R. and Jones, D. L. (2015) 'Consequential life cycle assessment of biogas, biofuel and biomass energy options within an arable crop rotation', *GCB Bioenergy*, 7(6), pp. 1305–1320. doi: 10.1111/gcbb.12246.

Styles, D., Yesufu, J., Williams, P., Bowman, M. and Luyckx, K. (2020) *Identifying the Sustainable Niche for Anaerobic Digestion in a Low Carbon Future*. Bangor University and Feedback Global. Available at: https://feedbackglobal.org/wp-content/uploads/2020/08/Styles-et-al-2020-Identifying-the-Sustainable-Niche-for-Anaerobic-Digestion-in-a-Low-Carbon-Future.pdf

Sustain (2016) *8.4m in UK too poor to eat | Sustain*, *Sustain*. Available at: https://www.sustainweb.org/news/voicesofthehungry/ (Accessed: 4 June 2020).

Tambone, F., Scaglia, B., D'Imporzano, G., Schievano, A., Orzi, V., Salati, S. and Adani, F. (2010) 'Assessing amendment and fertilizing properties of digestates from anaerobic digestion through a comparative study with digested sludge and compost', *Chemosphere*, 81(5), pp. 577–583. doi: 10.1016/j.chemosphere.2010.08.034.

Tasker, J. (2018) *Gove's new farm pollution controls: The details and reaction*, *Farmers Weekly*. Available at: https://www.fwi.co.uk/news/environment/goves-new-farm-pollution-controls-the-details-and-reaction (Accessed: 22 July 2020).

Tatum, M. (2017) 'Is anaerobic digestion eating up edible food?', *The Grocer*, July. Available at: https://www.thegrocer.co.uk/waste-not-want-not/is-anaerobic-digestion-eating-up-edible-food-/555612.article (Accessed: 30 July 2019).

Tax Justice Network (2019) *Corporate Tax Haven Index – 2019 Results*, *Tax Justice Network*. Available at: https://www.corporatetaxhavenindex.org/introduction/cthi-2019-results (Accessed: 8 June 2019).

Teagasc (2011) *Research Results on Alternative Uses for Pig Manure*. Cork: Teagasc, Pig Development Department, Animal & Grassland Research & Innovation Centre. Available at: https://www.teagasc.ie/media/website/publications/2011/Moorepark_AlternativeUsesForPigManure.pdf (Accessed: 26 February 2020).

Tesco (2020) *UK Food Waste Data 2019/20*, *Tesco PLC*. Available at: /sustainability/performance/data-tables/food-waste-data/uk-data/ (Accessed: 8 July 2020).

Thorpe, D. (2020) *Does AD pay off on smaller farms?*, *NatWest Business Hub*. Available at: https://www.natwestbusinesshub.com/content/does-anaerobic-digestion-pay-off-on-smaller-farms (Accessed: 9 March 2020).

Timonen, K., Sinkko, T., Luostarinen, S., Tampio, E. and Joensuu, K. (2019) 'LCA of anaerobic digestion: Emission allocation for energy and digestate', *Journal of Cleaner Production*, 235, pp. 1567–1579. doi: 10.1016/j.jclepro.2019.06.085.

Tonini, D., Hamelin, L., Alvarado-Morales, M. and Astrup, T. F. (2016) 'GHG emission factors for bioelectricity, biomethane, and bioethanol quantified for 24 biomass substrates with consequential life-cycle assessment', *Bioresource Technology*, 208, pp. 123–133. doi: 10.1016/j.biortech.2016.02.052.

Uwizeye, A., Gerber, P. J., Opio, C. I., Tempio, G., Mottet, A., Makkar, H. P. S., Falcucci, A., Steinfeld, H. and de Boer, I. J. M. (2019) 'Nitrogen flows in global pork supply chains and potential improvement from feeding swill to pigs', *Resources, conservation, and recycling*. Elsevier B.V. Available at: https://agris.fao.org/agris-search/search.do?recordID=US201900186675 (Accessed: 11 June 2020).

Vaughan, N. E. and Gough, C. (2016) 'Expert assessment concludes negative emissions scenarios may not deliver', *Environmental Research Letters*. IOP Publishing, 11(9), p. 095003. doi: 10.1088/1748-9326/11/9/095003.

Visiongain (2019) *Visiongain Report Researches Growth Opportunities within the $31.5 bn Anaerobic Digestion Market*, *PR Newswire*. Available at: https://www.prnewswire.co.uk/news-releases/visiongain-report-researches-growth-opportunities-within-the-31-5-bn-anaerobic-digestion-market-880274530.html (Accessed: 18 December 2019).

Whitlock, R. (2019) *ADBA renews its pre-election asks from the new Conservative Government*, *Renewable Energy Magazine*. Available at: https://www.renewableenergymagazine.com/biogas/adba-renews-its-preelection-asks-from-the-20191216 (Accessed: 17 December 2019).

Whittaker, C., Hunt, J., Misselbrook, T. and Shield, I. (2016) 'How well does Miscanthus ensile for use in an anaerobic digestion plant?', *Biomass and Bioenergy*, 88, pp. 24–34. doi: 10.1016/j.biombioe.2016.03.018.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F. and Wood, A. (2019) 'Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems', *The Lancet*, 393(10170), pp. 447–492.

World Biogas Association (2019a) *Biogas and Climate Change Commitment Declaration*. World Biogas Association. Available at: https://www.worldbiogasassociation.org/wp-content/uploads/2020/04/Biogas-and-Climate-Change-Commitment-Declaration.pdf (Accessed: 17 December 2019).

World Biogas Association (2019b) *Global Potential of Biogas: Executive Summary*. World Biogas Association. Available at: http://www.worldbiogasassociation.org/wp-content/uploads/2019/07/WBA-execsummary-4ppa4_digital.pdf (Accessed: 17 December 2019).

WRAP (2015) *Field experiments for quality digestate and compost in agriculture: Work Package 1 report – Effect of repeated digestate and compost applications on soil and crop quality*. WRAP. Available at: http://www.wrap.org.uk/sites/files/wrap/DC-Agri_Work_Package_1_-_Effects_on_Soil_and_Crop_Quality.pdf (Accessed: 1 October 2019).

WRAP (2016a) *Digestate and compost in agriculture (DC-Agri) project reports*, *WRAP*. Available at: http://www.wrap.org.uk/content/digestate-and-compost-agriculture-dc-agri-reports (Accessed: 1 October 2019).

WRAP (2016b) *Field experiments for quality digestate and compost in agriculture*. WRAP. Available at: http://www.wrap.org.uk/sites/files/wrap/WRAP_DC-Agri_research_summary.pdf (Accessed: 1 October 2019).

WRAP (2016c) *Field Experiments for Quality Digestate and Compost in Agriculture: Work Package 2 Report – Digestate Nitrogen Supply and Environmental Emissions*. WRAP. Available at: http://www.wrap.org.uk/sites/files/wrap/DC-Agri_Work_Package_2_-_Digestate_nitrogen_supply_and_environmental_emissions.pdf (Accessed: 1 October 2019).

WRAP (2019a) *Food for Thought at the ADBA National Conference*, *Anaerobic Digestion & Bioresources Association*. Available at: http://adbioresources.org/news/food-for-thought-at-the-adba-national-conference (Accessed: 17 December 2019).

WRAP (2019b) *Food Surplus and Waste in the UK – Key Facts*. WRAP. Available at: http://www.wrap.org.uk/sites/files/wrap/Food%20Surplus%20and%20Waste%20in%20the%20UK%20Key%20Facts%20%2822%207%2019%29_0.pdf (Accessed: 16 October 2019).

WRAP (2019c) *Food waste in primary production in the UK*. WRAP. Available at: http://www.wrap.org.uk/content/food-waste-primary-production-uk (Accessed: 23 August 2019).

van Zanten, H. H. E., Mollenhorst, H., Oonincx, D. G. A. B., Bikker, P., Meerburg, B. G. and de Boer, I. J. M. (2015) 'From environmental nuisance to environmental opportunity: housefly larvae convert waste to livestock feed', *Journal of Cleaner Production*, 102, pp. 362–369. doi: 10.1016/j.jclepro.2015.04.106.

Feedback regenerates nature by transforming the food system. To do this we challenge power, catalyse action and empower people to achieve positive change.

Published September 2020

Authors: Martin Bowman and Krysia Woroniecka
Additional research and editing: Karen Luyckx, Jessica Sinclair Taylor, Megan Romania and Carina Millstone.
Design: Garth Stewart
Infographics: Becky Elms and Lindsay Noble

With special thanks to David Styles and Jalil Yesufu (Bangor University), authors of the Life Cycle Assessment study, commissioned by Feedback, which forms the main basis of this report.

Suggested citation: Feedback (2020), Green Gas Without the Hot Air: Defining the true role of biogas in a net zero future. London.

www.feedbackglobal.org
@feedbackorg

Registered in England and Wales, charity number 1155064

FEEDBACK
FEEDING PEOPLE, BACKING THE PLANET