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Life cycle environmental impacts of generating electricity and heat from biogas produced by anaerobic digestion

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A B S T R A C T

Financial incentives in many European countries have led to a surge in anaerobic digestion (AD) installations to produce heat and/or electricity from biogas. This paper presents the life cycle environmental impacts of a system producing biogas from agricultural wastes by AD and co-generating heat and electricity in a combined heat and power (CHP) plant. The results suggest that this can lead to significant reductions in most impacts compared to fossil-fuel alternatives, including the global warming potential (GWP) which can be reduced by up to 50%. However, the acidification and eutrophication potentials are respectively 25 and 12 times higher than for natural gas CHP. The impacts are influenced by the type and source of feedstock, digestate storage and its application on land. Using energy crops such as maize instead of waste reduces the GWP owing to higher biogas yields, but eight out of 11 impacts increase compared to using waste feedstocks. If digestate is not used to displace artificial fertilisers, the majority of impacts are higher than from natural gas CHP. Some other bioenergy options have lower GWP than energy from biogas, including woodchip CHP plants. Implications for policy are discussed based on the results of the study.

1. Introduction

Anaerobic digestion (AD) utilises biomass under anaerobic conditions to produce biogas, a mixture containing between 50 and 75% of methane with the rest being carbon dioxide [1]. The biogas can be used to generate heat and/or electricity. As a source of renewable energy, AD has the potential to improve security of energy supply and help reduce greenhouse gas (GHG) emissions. It is also useful as an energy source that can be accessed on demand, unlike some other renewables such as wind and solar, which are more intermittent. AD is of particular interest to farms as it can use agricultural waste, converting it into both energy and fertilisers.

Despite being an established technology, the growth in AD installations in Europe has started only relatively recently, with the introduction of financial incentives. Currently, 29 European countries have incentives that promote electricity generation from biogas. An example is Germany with around 7000 AD plants in 2010 [2,3], many of which are small (<75 kWe) and farm-based [4]. The AD operators receive between 12 and 25 €cents for each kWh of electricity generated [5]. Italy is another country where AD benefits from financial incentives with payments of 8.5–23 €cents/kWh, depending on capacity [6]; to date, there are around 1000 AD installations nationally [7].

In the UK, the growth in AD installations was kick-started by the introduction of the feed-in tariffs (FITs) in 2010 and the Renewable Heat Incentive (RHI) in 2011 which pay for electricity and heat generation, respectively [8]. Both schemes were introduced to help towards the UK's aim of reducing greenhouse gas (GHG) emissions by 80% by 2050 [9] as well as the amount of waste sent to landfill [10]. As of 2013, AD was the only bioenergy technology to receive FIT subsidies in the UK [11]. Combined heat and power (CHP) plants smaller than 2 kW are also covered by the scheme but the use of biomass is not mandated. Other bioenergy electricity generators are instead subsidised by the Renewables Obligation [12]. As shown in Table 1, at 15.16 pence per kWh (~18.20 €cents/kWh), the FITs are highest for AD systems smaller than 250 kW, reducing to 9.24 p/kWh for the installations larger than 500 kW. RHI only applies to smaller units (<200 kWh_{th}) and pays currently 7.3 p/kWh. As a result, there are 123 AD installations in the UK, the large majority of which (97%) are fitted with combined heat and power plants (CHP). Of these, 43% are installed at farms, 38% are community and 19% industrial plants [13]. Overall, more than half of the installations are over 500 kWe, a quarter are between 250 and 500 kWe with the rest being smaller than 250 kWe [13].

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Table 1
Feed-in-tariff (FIT) and renewable heat incentive (RHI) payments for AD installations in the UK [11].

Scale	FITs (pence/kWh)	RHI (pence/kWh)
≤250 kW	15.16	7.3[a]
>250 kW ≤ 500 kW	14.02	–
>500 kW	9.24	–

[a] For the RHI, the payment applies to AD capacity smaller than 200 kWh_{th}.

Although the UK is currently well behind some other European countries in terms of the number of AD installations, this is changing fast driven by the subsidies. However, whilst AD has a potential to help reduce GHG emissions from energy generation, its environmental impacts on a life cycle basis are uncertain and depend largely on the feedstocks used. A variety of biomass sources can be used in AD, including agricultural wastes such as manure and straw but also cereal crops such as maize and wheat. In some countries, such as Germany and Italy, for example, cereals are the main feedstock used for AD [3,7]. Although agricultural waste is available and would be more sustainable to use, cereals have higher biogas yields, which in turn leads to more electricity being generated, thus providing higher returns on investment. However, although data are scant, there is some evidence that in the areas where biogas production is more widespread, biomass prices and the value of land are increasing [7], driving competition with food production. Thus, this is an example of unintended consequences that policy can have through subsidies, promoting unsustainable practices.

Several life cycle assessment (LCA) studies have been carried out so far to estimate the environmental impacts of biogas from AD and related energy generation. Examples include using feedstocks such as organic household waste in Switzerland [14], agricultural wastes in Sweden [15], sewage in Spain [16], cereal crops in Germany [17] and Italy [7] and manure in the UK [18]. This paper considers the use of mixed farm wastes in a state-of-the art system comprising an AD and a CHP plant based in the UK. As far as we are aware, this is the first study to consider both electricity and heat production from mixed farm wastes – the only UK study found in literature [18] considered only manure as feedstock and heat as an energy output. Furthermore, through sensitivity analysis, we also consider how the impacts are affected if cereals such as maize are used instead of waste.

2. Methodology

LCA has been used as a tool to estimate the environmental impacts of the AD-CHP system, following the ISO 14040/14044 methodology [19,20]. The methodology, data and the assumptions are described in more detail in the following sections.

2.1. Goal and scope of the study

The goal of the study is to estimate the life cycle environmental impacts of electricity and heat co-generated in a CHP plant using biogas produced in an AD reactor. A further aim is to compare the impacts of the AD-CHP system with electricity and heat generation from fossil-based alternatives typically used at farms: natural gas CHP, electricity from the grid and heat from natural gas or oil boilers. An AD-CHP system installed at a dairy farm in the UK is considered. The AD is fed with a combination of different farm wastes comprising manure, cheese whey, maize silage and fodder beet.

The system studied here is illustrated in Fig. 1. As shown, the system boundary includes collection of farm waste from different parts of the farm, production of biogas in the AD plant, co-generation of electricity and heat in the CHP plant as well as storage and use of digestate from AD as a fertiliser.

The functional unit is defined as ‘co-generation of 1 MWh of heat and electricity’ with the ratio of electricity to heat equal to 1:1.4. All the heat and some electricity generated are used by the farm, with the surplus electricity exported to the national grid. The system is described in more detail below, followed by a description of the fossil-fuel systems with which it is compared.

2.2. Description of the systems

2.2.1. AD-CHP system

All the waste used for AD is generated onsite and, after collection by trucks from various parts of the farm, it is fed into an on-site hopper and mixer. A total of around 14 tonnes per day of waste is fed into the AD, of which a half is manure with the rest split equally between cheese whey, waste maize silage and fodder beet (see Table 2). The feedstock then passes through a macerator before being pumped into an 800 m^3 anaerobic digester tank. Within the digester, the feedstock is agitated and heated up to 40 °C [21,22] in the absence of oxygen to produce 2027 Nm^3 of biogas per day. Based on the daily consumption of 14 t of feedstock, this is equivalent to a biogas yield of 145 Nm^3/t feedstock. Assuming the average content of methane in biogas of 60% [1], the methane yield is 87 Nm^3/t feedstock.

The liquid digestate generated in the AD tank is pumped out into a lagoon and stored for use on the farm as fertiliser. The solid digestate is removed and loaded onto a trailer to be used as fine compost. The AD produces enough liquid and solid digestate to reduce the use of artificial fertilisers on the farm by 75%.[1]

Biogas is piped from the top of the AD to a 350 m^3 gas storage tank and then to the CHP. The CHP unit has a capacity of 170 kW_{el} and 200 kW_{th} and it produces 1.08 GWh electricity and 1.48 GWh of heat per year (2.56 GWh of energy in total) from 740,000 Nm^3/yr of biogas. Thus, per m^3 of biogas, the plant generates 1.46 kWh_{el} and 2 kWh_{th}. For the functional unit of 1 MWh, the plant generates 422 kWh_{el} of electricity and 578 kWh_{th} of heat from 289 Nm^3 of biogas. The total efficiency of the CHP plant is 85%, with the efficiency of electricity generation of 39% and heat 46% [23]. The overall efficiency of the system with regard to the feedstock conversion to electricity and heat is estimated at around 26% [24,25].[2]

The majority of the heat (71% or 412 kWh_{th}/MWh)[3] is used to heat the farm buildings and the drinking water for the cows, while the rest (29%) is fed back to the digester to keep the desired temperature; the latter is equivalent to around 48 m^3 of gas per MWh of energy (or per 289 Nm^3 gas) produced. Around 218 MWh/yr of the electricity is used to power the farm, including the AD facility (see Table 2), with the remainder (~862 MWh/yr) exported to the grid.

[1] Copys Green Farm, England. Personal communication.

[2] HHV = 1.973 × [100 − Ash (%)] × [100 − Moisture Content (%)] [24]. Manure: Moisture Content (MC) = 82.5%, Ash (A) = 25% ⇒ HHV = 2590 kJ/kg. Maize: MC = 10%, A = 3% ⇒ HHV = 17,224 kJ/kg. Fodder beet: MC = 10%, A = 7% ⇒ HHV = 16,514 kJ/kg; Cheese whey: HHV = 1000 kJ/kg [25]. The ratio of manure to other feedstock = 0.5:0.5. The ratio of fodder beet to maize to cheese whey = 0.33:0.33:0.33: Total HHV of all feedstocks = 2590 × 0.5+(17,224 × 0.33 + 16,514 × 0.33 + 1000 × 0.33) × 0.5 = 7020 kJ/kg. Theoretical heat and electricity generation = 7020 MJ/t × 10^{-3} GJ × 5110 t/yr = 35,870 GJ/yr = 9.96 GWh/yr. Annual generation = 1.08 GWh_{el} + 1.48 GWh_{th} = 2.56 GWh. Feedstock conversion efficiency: 2.56 GWh/9.96 GWh = 25.7%.

[3] Electricity to heat ratio: 1:1.4 ⇒ 1 MWh_{el+th} = 0.422 MWh_{el} + 0.578 MWh_{th}. 0.578 MWh_{th} × 0.8 = 0.46 MWh_{th}.

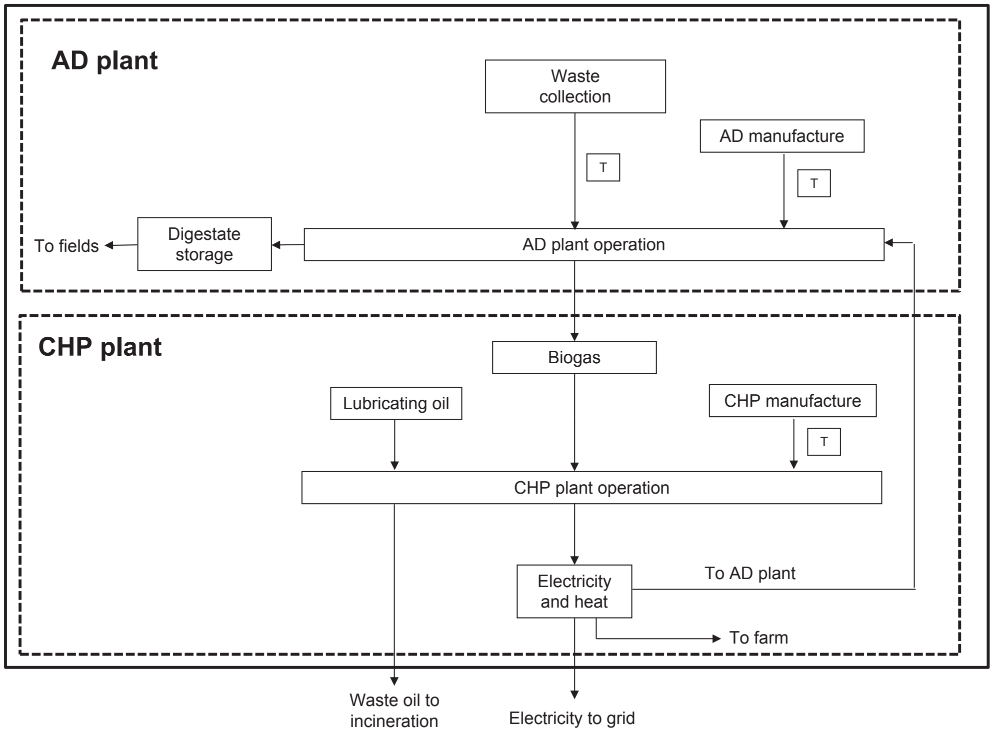

Fig. 1. System boundary for the AD-CHP system (T = transport).

2.2.2. *Fossil fuel alternatives*

Two common alternatives to the AD-CHP system are considered:

i) natural gas CHP; and
ii) electricity supplied from the grid and heat generated by either a gas or oil boiler.

These are illustrated in Fig. 2 and include fuel production and delivery to the plant, plant construction and operation to generate heat and electricity, and eventual decommissioning and disposal of the plants. To enable fair comparisons, it is assumed that the same amount of heat and electricity is generated as in the AD-CHP system. The electricity mix is shown in Fig. 3 [26].

2.3. *Data and assumptions*

A summary of data used in the study is given in Table 2. The feedstock and operational data for the AD and CHP plants have been obtained from the farm owners. All background data are from the Ecoinvent database v2.2 [27]. Since the data for construction materials for the AD and CHP plants in Ecoinvent correspond to smaller plants (300 m^3 AD and 160 kW_{el} CHP), the environmental impacts from their manufacture had to be estimated by scaling up to the 800 m^3 AD and 170 kW_{el} CHP plants considered in this study. This has been carried out following the approach used in scaling up process plants [28]:

$$E_2 = E_1 x \left(\frac{C_2}{C_1}\right)^{0.6}$$

where:

E_2 environmental impacts of the larger plant
E_1 environmental impacts of the smaller plant
C_2 capacity of the larger plant
C_1 capacity of the smaller plant
0.6 scaling factor.

No environmental impacts are considered for the feedstock as it is made up from waste.

The system produces digestate which can be used as fertiliser. In this study, the farm owners estimate that they save 27 tonnes of an ammonium sulphate and nitrate mix per year so that the system has been credited for displacing this amount of artificial fertiliser. Note that this saving refers to the use of digestate compared to the use of manure as fertiliser, before manure started to be used for AD. In the absence of real data, the impacts from applying digestate on the land are assumed to be similar to that of artificial fertiliser for the same content of nitrogen, phosphorous and potassium. However, this may not be the case owing to the different forms of the nitrogen and the digestate being more volatile than artificial fertiliser.

Digestate is stored in an open-air lagoon from which both ammonia and methane are released. These are assumed at 8.9 kg/MWh for methane and 0.23 kg/MWh for ammonia; further 1.35 kg/MWh of ammonia is released during digestate spreading [29].

At the end of their useful lifetime, here assumed to be 20 years, the AD and CHP plants are dismantled and the component material either landfilled, recycled or incinerated (see Table 2).

3. Results and discussion

The systems have been modelled using Gabi LCA software V4.4 [30] and the impacts estimated using the CML 2011 method [31]. The results are shown in Figs. 4–7. As can be seen from Fig. 5, the impacts are dominated by biogas production in AD. The following sections discuss the results for each impact in turn.

Table 2
Summary of data and data sources.

Data	Amount	Source
Inputs to AD plant		
Manure	7 t/day	Farm owners
Other waste[a]	7 t/day	Farm owners
Heat (from CHP)	169 kWh/MWh	Farm owners
Electricity (from CHP)	44 kWh/MWh	[27]
Concrete	8.5 dm^3/MWh	[27]
Reinforced steel	0.71 kg/MWh	[27]
Chromium steel	85 g/MWh	[27]
Copper	8 g/MWh	[27]
Laminated timber	0.6 dm^3/MWh	[27]
High-density polyethylene	3 g/MWh	[27]
High-impact polystyrene	37 g/MWh	[27]
Polyvinyl chloride	5 g/MWh	[27]
Synthetic rubber	20 g/MWh	[27]
Outputs from AD plant		
Biogas	289 Nm^3/MWh (145 Nm^3/t feedstock)	Farm owners
Digestate	4289 t/yr	Farm owners
Artificial fertiliser displaced	27 t/yr *Future: 54 t/yr*	Farm owners
Inputs to CHP		
Lubricating oil	168 g/MWh	[27]
Reinforced steel	185 g/MWh	[27]
Low-alloyed steel	13 g/MWh	[27]
Chromium steel	10 g/MWh	[27]
Cast iron	56 g/MWh	[27]
Copper	9.4 g/MWh	[27]
Polyethylene	3.5 g/MWh	[27]
Polyvinyl chloride	0.34 g/MWh	[27]
Synthetic rubber	0.28 g/MWh	[27]
Outputs from CHP		
Electricity output	422 kWh/MWh	Farm owners
Heat output	578 kWh/MWh	Own calculations based on farm owner's data
CHP efficiency	85%	[23]
Transport of AD-CHP plants components		
Freight rail	120 km	[27]
Lorry	35 km	[27]
End-of-life waste management		
Concrete	Landfilled	[27]
Plastics	93% incinerated; 7% landfilled	[27]
Rubber	100% incinerated	[27]
Waste oil	100% hazardous waste incineration	[27]
Fossil fuel alternatives		
Electricity from UK grid or natural gas CHP	422 kWh	[26,27]
Heat from natural gas boiler, oil boiler or natural gas CHP	578 kWh	[27]

[a] Equal proportion of waste maize silage, fodder beet and cheese whey assumed, i.e. 2.33 t/day each.

3.1. AD-CHP system

3.1.1. Abiotic depletion potential (ADP)

As seen in Fig. 4, there is an overall saving in depletion of elements of 18 mg Sb eq./MWh. This is largely due to the credits for artificial fertilisers displaced by the digestate. Some reduction (22%) in ADP is also due to the credits for recycling of the plant construction materials. At the level of the AD and CHP plants, their construction is the major contributor to this impact, ranging from 70% for AD to >95% for the CHP (see Figs. 6 and 7).

As also indicated in Fig. 4, 20 MJ of fossil fuels are depleted per MWh generated. The majority (70%) of this is due to the energy used for operation of AD (see Table 2 and Fig. 6). By contrast, 75% of fossil fuel depletion for the CHP plant is due to the construction of the plant which in turn is due to electricity used for steel and concrete.

3.1.2. Acidification and eutrophication potentials (AP and EP)

Ammonia emissions are responsible for 95% of AP and 97% of EP, estimated at 3.14 kg SO_2 eq./MWh and 672 g PO_4 eq./MWh, respectively (Fig. 4). The ammonia is produced in the liquid digestate and escapes during its open-air storage.

3.1.3. Global warming potential (GWP)

As shown in Fig. 4, the total GWP is estimated at 222 kg CO_2 eq./MWh, the vast majority (86%) of which is due to methane emissions from the digestate during its storage. Carbon dioxide emissions from biogas combustion in the CHP are not considered as they are biogenic in nature.

3.1.4. Human and eco-toxicity potentials

The use of coal as an energy source for manufacture of the plants is the major contributor to water toxicity, owing to short-term emissions of nickel and long-term emissions of beryllium, cobalt, copper and vanadium. This results in 2.9 kg DCB eq./MWh of freshwater aquatic eco-toxicity (FAETP), with the largest individual contributor being nickel emissions to freshwater (41%). It also results in 3 t DCB eq./MWh of marine water eco-toxicity (MAETP), with the greatest individual contributor being beryllium (38%).

The chromium steel used in the manufacture of the AD plant is the hotspot for the terrestrial eco-toxicity potential (TETP), contributing 84% of the 157 g DCB eq./MWh, and 54% to the human toxicity potential (HTP) of 4.1 kg DCB eq./MWh. This is because of chromium emissions during the production of ferrochromium used for the plant manufacture.

3.1.5. Ozone depletion potential (ODP)

Ozone depletion of 0.08 mg R11 eq./MWh is caused by the release of halons such as bromotrifluoromethane during the combustion of the biogas in the CHP plant. Thus the generation of heat and electricity from biogas combustion is the main contributor (57%) to the ODP. Other contributors include manufacture of AD and CHP, with 17% each.

3.1.6. Photochemical oxidant creation potential (POCP)

This impact is estimated at 74 g C_2H_4 eq./MWh, largely (69%) owing to the emissions of methane from the digestate storage.

In summary, biogas production is the major contributor to GWP, AP, EP, ODP and POCP, largely because of the emissions from digestate storage. Manufacture of the AD and the CHP plants is the largest contributor to the toxicity-related impacts and the depletion of elements. Fossil fuels are also depleted during manufacture of the plants owing to the use of energy.

3.2. Comparison to heat and electricity generation from fossil fuels

Currently, the vast majority of heat and electricity in the UK is supplied by natural gas boilers and the national grid, respectively. If heat is required in an area which is remote and off the gas grid, oil may be used instead. Therefore, this section compares the impacts of the AD-CHP system discussed above with its fossil alternatives. The life cycles of the alternative systems were described in section 2 and the sources of data in Table 2.

The results in Fig. 4 indicate that replacing a fossil-fuel system with heat and electricity generated in the AD-CHP system considered here could lead to significant reductions in most impacts. Notably, the key driver for biogas production – GWP – is reduced

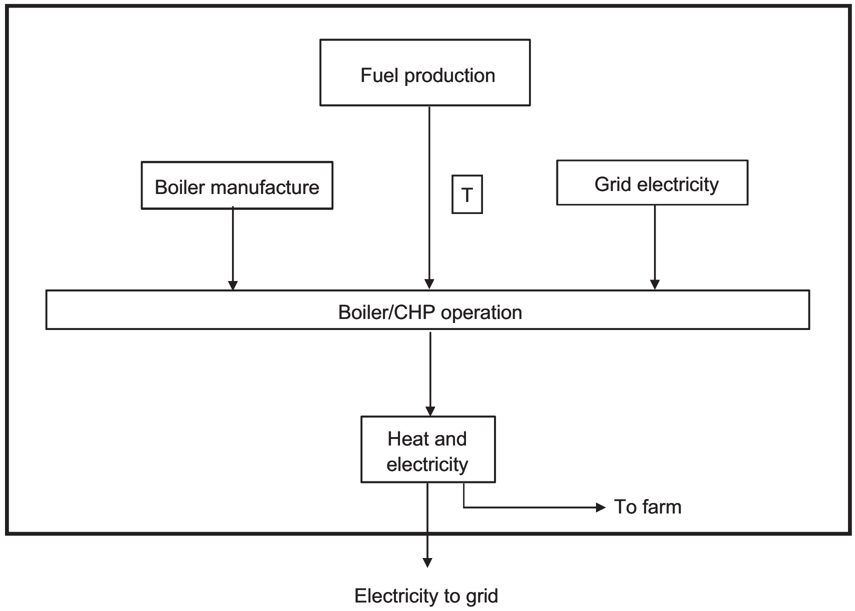

Fig. 2. System boundary for the gas and oil boilers and CHP systems (T – transport).

by 34% compared to the natural gas CHP and by 47%–50%, compared to the other two alternatives. More significant savings are achieved for fossil fuel depletion and ozone layer depletion, with almost 100% reduction across all the fossil alternatives. Furthermore, the AD-CHP system also has much lower (~95%) human and eco-toxicity potentials than either of the two electricity-boiler systems. The reductions in the toxicity potentials are smaller in comparison to the natural gas CHP, ranging from just 1% for freshwater aquatic toxicity to 19% for human and 60% for marine toxicity. On the other hand, the AD-CHP system has 55% higher terrestrial eco-toxicity than the gas CHP; this is due to the additional construction materials needed for the AD unit. Furthermore, the photochemical oxidant creation potential is 2.9 times higher for the AD-CHP plant than for the gas CHP.

Therefore, in summary, the results suggest that AD-CHP is the best option for nine impacts out of 11 considered when compared to the electricity-boiler systems and seven impacts when compared to gas CHP. Gas CHP is the second best option. The most notable difference between the AD-CHP and the other systems is found for acidification and eutrophication potentials, which are 25 and 12 times higher, respectively, than for the next best option – gas CHP system. Compared to the electricity with gas and oil boilers, the difference in these impacts is smaller, but still significant: around 2.6 and 1.7 times, respectively. As mentioned in the previous section, the main reason for these impacts is the release of ammonia during the open-air storage of digestate. Reductions in these impacts may be achieved through better handling of digestate to limit the emissions of ammonia. This is explored further in the sensitivity analysis in section 5. Prior to that, we compare the results of this study with those found in literature.

4. Comparison with other studies

Although several life cycle assessment studies of AD have been carried out, direct comparison with the results in the current study is not possible owing to different functional units, types of systems (most consider AD only without CHP), assumptions and life cycle impacts assessment methodologies used. Therefore, it was possible to compare the results with only two other studies, one carried out by Blengini et al. [32] and another by Buhle et al. [17]. The former investigated the co-production of electricity and heat from biogas produced from a mixture of manure and miscanthus in Italy and the latter assessed a similar system but using rye and maize silage in Germany.

As indicated in Fig. 8, the results compare well, given different feedstocks, assumptions and geographical locations of the system. At 222 kg CO_2 eq./MWh, the GWP estimated in this study is slightly higher than in either of the two studies, which report 168 kg CO_2 eq./MWh [32] and 137 kg [17]. The difference may be because the former study included a significant soil uptake of carbon which exceeded direct carbon emissions from agricultural activities, while Bhule et al. [17] assumed lower emissions of methane.

There is a close agreement for the acidification potential between Blengini et al. [32] and this study: 3.8 and 3.14 kg SO_2 eq./MWh, respectively. The former result may be slightly higher owing to the higher assumed ammonia emissions from digestate spreading. This also affects the eutrophication potential, which is

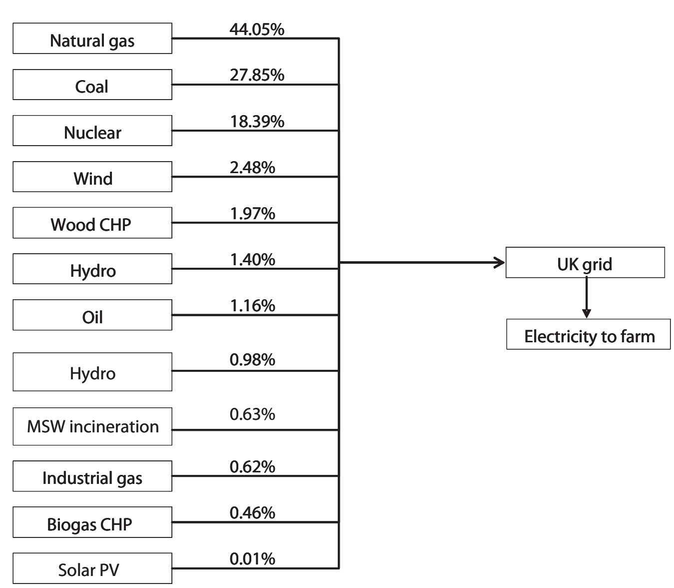

Fig. 3. UK electricity grid (based on data from Ref. [10]).

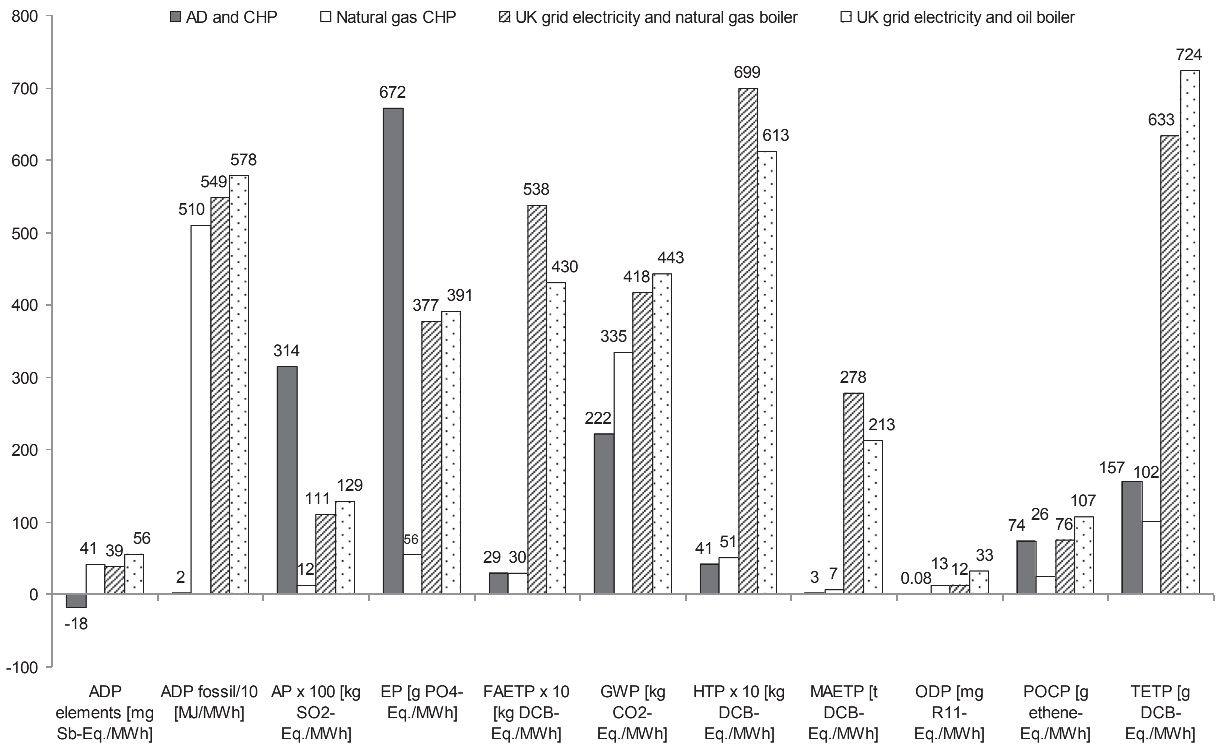

Fig. 4. The environmental impacts associated with the generation of 1 MWh of electricity and heat from the AD-CHP system compared to the fossil fuel alternative. [ADP elements: Abiotic depletion potential for elements; ADP fossil: Abiotic depletion potential for fossil fuels; AP: Acidification potential; EP: Eutrophication potential; FAETP: Freshwater aquatic eco-toxicity potential; GWP: Global warming potential; HTP: Human toxicity potential; MAETP: Marine aquatic eco-toxicity potential; ODP: Ozone depletion potential; POCP: Photochemical oxidant creation potential; TETP: Terrestrial eco-toxicity potential. DCB: dichlorobenzene; R11: trichloroflurومethane. Some impacts have been scaled to fit and the factors shown against relevant impacts indicate the scaling factor and operation performed during the scaling.]

much higher (1008 g PO_4/MWh) than in the current study (672 g). On the other hand, the acidification potential estimated by Buhle et al. [17] is significantly lower at 1.41 kg SO_2 eq./MWh. This may be because the authors did not consider the use and storage of the digestate and its associated ammonia emissions. This could also be the reason for a much lower value for the AP (215 g PO_4 eq./MWh).

Finally, the photochemical oxidant creation potential in Blengini et al. [32] is much lower than in this study: 16.8 g C_2H_4 eq./MWh compared to 73.7 g. Again, the reason for this may be the differences in the assumptions for methane emissions from digestate during storage.

As mentioned in the introduction, only one other UK-specific LCA study of AD was found, which assessed the environmental impacts of producing biogas from manure for heat production at a farm in England [18]. Since the two systems are different, direct comparison is not possible; furthermore, their study used a different life cycle impact assessment methodology, preventing quantitative comparison of the results. Nevertheless, the authors also found high acidification and eutrophication from ammonia emissions as well as a reduction across the impacts owing to the system credits for digestate replacing artificial fertilisers.

5. Sensitivity analysis

This section explores the effect on the results of different parameters which could potentially affect the impacts significantly. These are related to the use of different feedstocks for biogas production, efficiency of energy generation in the CHP plant, the amount of digestate used to displace artificial fertiliser, and

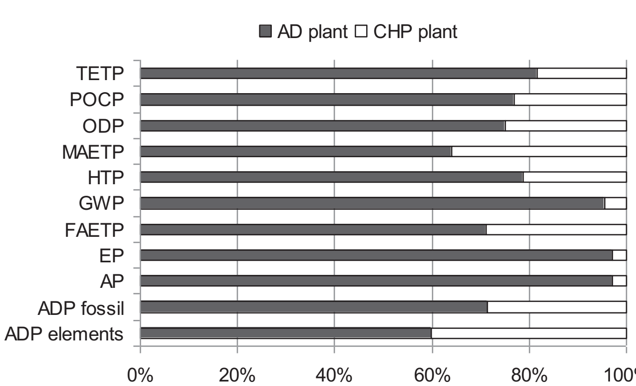

Fig. 5. Contribution analysis for the AD-CHP system. [For impacts nomenclature, see Fig. 4.]

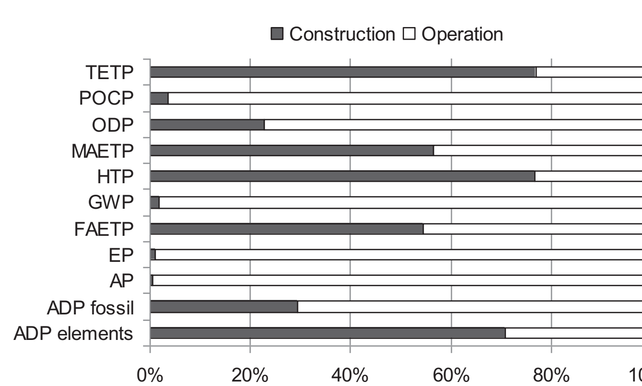

Fig. 6. Contribution analysis for the AD plant (biogas production stage). [For impacts nomenclature, see Fig. 4.]

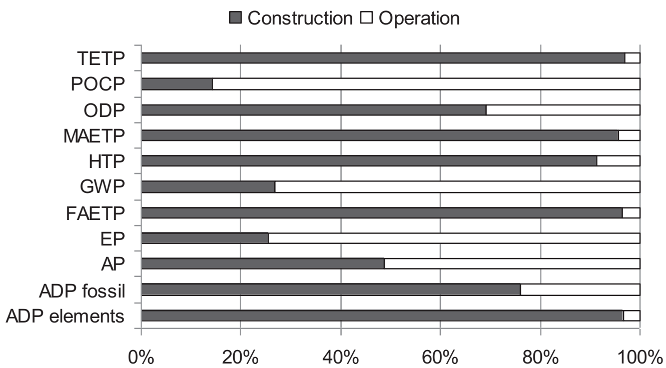

Fig. 7. Contribution analysis for the CHP plant (heat and electricity generation stage). [For impacts nomenclature, see Fig. 4.]

digestate storage and application on land. The findings are discussed below for each parameter in turn.

5.1. *Alternative feedstocks*

As mentioned in the introduction, the financial subsidies in Europe are driving the use of agricultural crops such as cereals for biogas production. Therefore, we investigate here how the impacts from the AD-CHP system change if instead of using maize silage and fodder beet as waste, these are grown specifically as energy crops. Two illustrative cases are considered:

i) a mixture of maize and beet as energy crops with waste (manure and cheese whey); and
ii) maize grown as energy crop and used as the only feedstock.

The LCA data for cultivation of maize and beet are from Ecoinvent [27].

5.1.1. *Maize and beet as energy crops mixed with manure and whey*

This analysis assumes the same AD-CHP system as before, but instead of maize and beet being waste, they are now assumed to be grown specifically to produce biogas for energy generation. As before, 2.33 t/day each of maize and beet are mixed with manure and cheese whey (see Table 2). The results are compared in Fig. 9 with the base case and for context, with the best fossil-fuel alternative considered here, i.e. natural gas CHP.

It is not surprising to find out that the impacts go up when agricultural crops instead of waste are used since the environmental impacts of their cultivation are now included within the system boundary (Fig. 9). The greatest increase is observed for ozone layer depletion and terrestrial eco-toxicity which are respectively 22 and 10 times higher than in the base case. All other toxicity-related impacts are 3 times higher. Further, depletion of fossil fuels is 8 times greater while depletion of elements increases from a negative value of −18 to 39 mg Sb eq./MWh. Global warming potential and acidification are each 11% higher and eutrophication 33%.

Compared to natural gas CHP, the AD-CHP system using maize and beet crops is significantly worse for five out of 11 impacts, in addition to the previously worse performance on acidification and eutrophication: terrestrial eco-toxicity is 16 times higher and all other toxicities between 27% (marine) and 2.8 times (freshwater). Photochemical oxidant creation potential is 3.3 times greater. However, AD-CHP is still a better option for depletion of elements (7%), fossil fuels (27 times), global warming (25%) and ozone layer depletion (7.4 times).

Next, we examine how the impacts change when all the waste feedstock is replaced by maize as energy crop.

5.1.2. *Maize as energy crop*

Methane yield and digestate nutrient content vary with the feedstock used. If maize alone is used instead of the feedstock considered in the base case, methane yield would almost double from 87 to 164 Nm^3/t [33]. This means that much less feedstock is required per MWh energy generated: 4.8 t/day compared to 14 t/day in the base case. Furthermore, 35 t/yr of artificial fertiliser would be displaced instead of 27 t/yr, owing to an increase in nitrogen content in the digestate [33].[4]

The results shown in Fig. 9 indicate that using maize instead of the waste leads to an increase in eight out of 11 impacts. Notably, terrestrial eco-toxicity is 18 times and ozone layer depletion 14 times higher than when using waste. Fossil fuel depletion increases by 5 times. The remaining toxicity impacts all go up by between 39% for human and around 3 times for freshwater and marine aquatic toxicity. Eutrophication is higher by 16%. Furthermore, there is no longer a saving in the depletion of elements which increase from −18 to 14 mg Sb eq./MWh. All these increases are due to the impacts of maize cultivation which are high enough to counter the positive effects of almost doubling the methane yield and the higher credits for fertiliser displacement than in the base case. However, for some impacts these positive effects are still larger than the additional impacts from maize: the global warming potential decreases by 38%, while acidification and photochemical oxidant creation are both around 30% lower than when using waste feedstock.

It can also be observed from Fig. 9 that, compared to natural gas CHP, two impacts become much higher when using maize than waste feedstock: terrestrial eco-toxicity is 28 times higher and freshwater eco-toxicity 3 times. With waste feedstock, terrestrial eco-toxicity was 1.6 times higher for AD-CHP while freshwater eco-toxicity was similar for both systems. However, there are further gains in the global warming differential between the AD-CHP system using maize and gas CHP: the former is 2.4 times lower compared to 1.5 times lower from the AD-CHP system using waste feedstock.

In summary, there are greater savings in the global warming potential by using maize as an energy crop compared to using waste. However, these come at the expense of eight other environmental impacts as discussed above. Thus, there is a danger that continuing with the policy of subsidising use of food crops for biogas production will increase other environmental impacts as well as causing competition with food production and related socio-economic consequences. Therefore, as these results suggest, using agricultural crops for biogas production is not environmentally sustainable and policy should not encourage this practice.

5.2. *CHP efficiency*

Further analysis was conducted to find out how the CHP efficiency affects the impacts and how much below 85% it could be still to outperform the fossil-fuel alternatives. Comparison with the grid electricity and natural gas boiler system is considered, as the most common of the three fossil-based alternatives in the UK. There are two impacts in which low CHP efficiency could potentially result in this fossil-fuel system outperforming AD-CHP: the global warming and photochemical oxidant creation potentials. There are two reasons for this: first, the CHP operation stage is the hotspot for

[4] Digestate from maize has a nitrogen content of 1.8 kg/t. At 5110 t/yr of maize, this equates to 9.2 t N/yr. Artificial fertiliser is assumed to contain 26% N so that the total amount of fertiliser displaced is: 9.2 t/yr ÷ 0.26 = 35 t/yr.

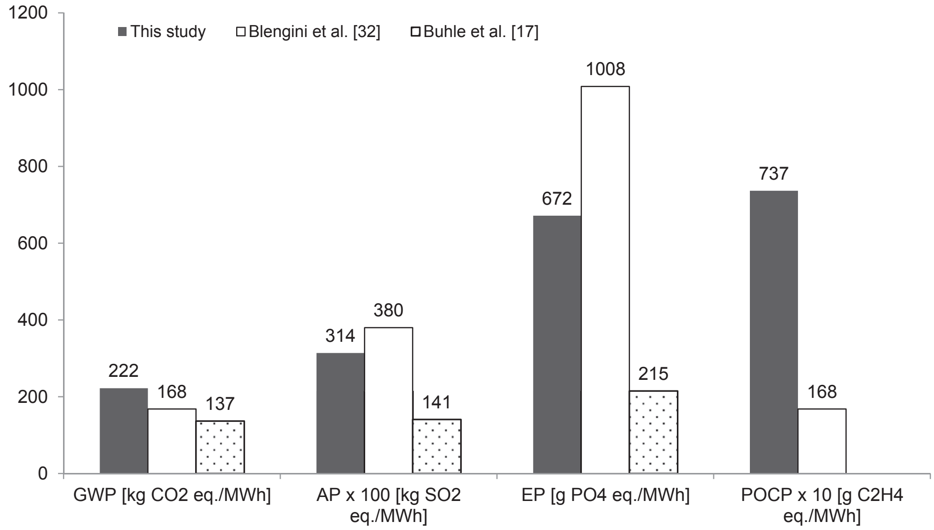

Fig. 8. Comparison of the results of this study with literature. [POCP was not considered in the Buhle et al. [17] study. For impacts nomenclature, see Fig. 4. AP and POCP have been scaled to fit by multiplying the original values with the factors shown against relevant impacts.]

these impacts (see Fig. 7), related directly to the amount of energy generated. Secondly, the difference between the two systems is lowest for these two impacts with GWP being 45% lower for AD-CHP and POCP only 2.5% (see Fig. 4).

The range of the CHP efficiencies and the resulting effect on the GWP and POCP are shown in Fig. 10. The cross-over point at which the two systems have equal GWP is the efficiency of 47%, below which the AD-CHP system would have higher GHG emissions per MWh than the fossil-fuel alternative. Arguably, the efficiency of 47% and below is too low for CHP so that the results can be considered robust with respect to the GWP. For the POCP, the cross-over point is the efficiency of 72% so that it is conceivable that grid electricity and gas boiler could outperform the AD-CHP system if the CHP plant is run at less than an optimal efficiency. For the other impacts, unrealistic increases or decreases in efficiency are required for the ranking of the systems to change. For example, for terrestrial eco-toxicity to be lower for the fossil fuel alternative than for the AD-CHP system, the CHP efficiency would have to be below 25%. Therefore, it could be concluded that, overall, the CHP efficiency does not influence the results to the point of changing the ranking of the options.

5.3. Displacement of artificial fertilisers by digestate

The use of digestate as a fertiliser means that the farm uses significantly less artificial fertiliser. As mentioned earlier, 27 t/yr of fertiliser is saved, compared to when manure was used as fertiliser instead of digestate. The farm owners estimate that this could double to 54 tonnes in future owing to improvements in the storage and application of liquid digestate. These improvements aim at

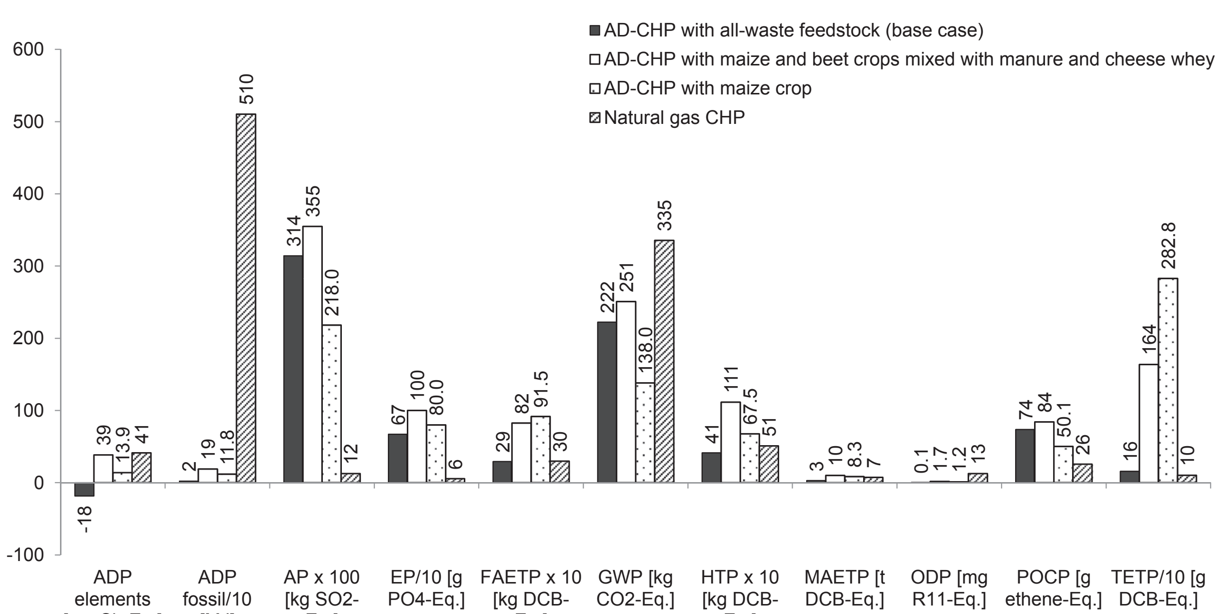

Fig. 9. Effect of different feedstocks on the impacts. [All impacts per MWh. For impacts nomenclature, see Fig. 4. Some impacts have been scaled to fit and the factors shown against relevant impacts indicate the scaling factor and operation performed during the scaling.]

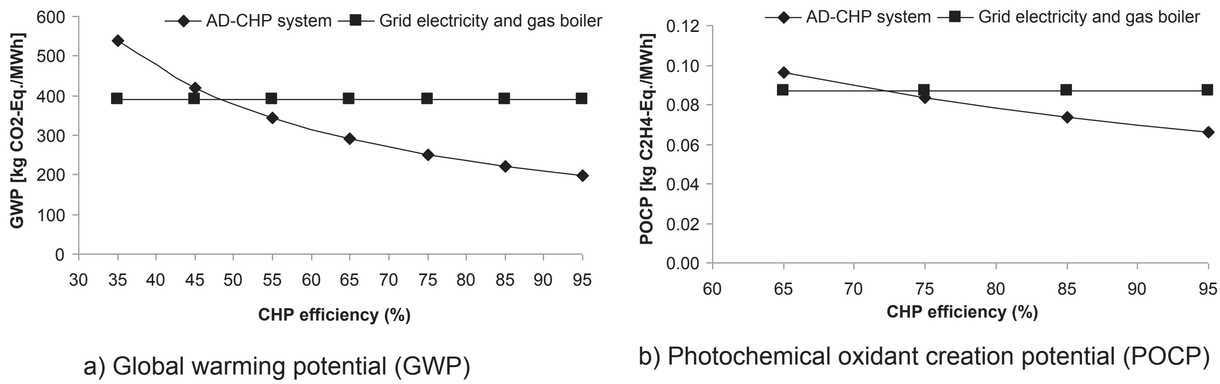

Fig. 10. Effect of CHP efficiency on GWP and POCP of the AD-CHP system and comparison with the electricity and gas boiler system. [CHP efficiency in the base case: 85%.]

increasing the nutrient value of the digestate by reducing the loss of nitrogen and applying it more effectively.

Therefore, in this section we examine how the impacts from the AD-CHP system would be affected if the amount of digestate were to double and compare the findings to the base case results presented in section 3. A further case is considered in which no credit is given to the system for displacing the artificial fertilisers. The fertiliser being displaced is assumed to be a 50:50 mix of ammonium nitrate and sulphur compounds containing 26% N and 12% S.

The results in Fig. 11 suggest that doubling the amount of digestate spread on farmland would lead to significant reductions in a number of impacts, notably fossil and ozone layer depletion as well as human, marine and terrestrial toxicity, all of which become negative. Freshwater eco-toxicity is also reduced significantly (by 75%) with a more modest reduction observed for the GWP (10%). These reductions are due to the reduction in fossil fuel use in the production of fertilisers. However, the eutrophication, acidification and photochemical oxidant creation potentials remain relatively unaffected by the amount of fertiliser displaced. This is because these impacts are mainly due to ammonia and methane emissions from the digestate storage and spreading.

If, on the other hand, no credits are given for the displacement of the fertiliser (or in other words, if digestate is not used on farmland), then the majority – eight out of 11 – of impacts from the AD-CHP system are higher than from the best fossil-fuel alternative (natural gas CHP) ranging from 22% higher depletion of elements to 26 times higher acidification (see Fig. 11). However, the GWP is still lower (by 27%) as are the fossil fuel and ozone layer depletion potentials (2.9 and 9 times lower, respectively).

5.4. Digestate storage

The findings of this study indicate that open-air digestate storage leads to the high acidification and eutrophication potentials owing to ammonia leakage. Additionally, methane escaping during the storage contributes to the global warming and photochemical oxidant creation potentials. These impacts could be reduced by storing the digestate in covered tanks and capturing methane and

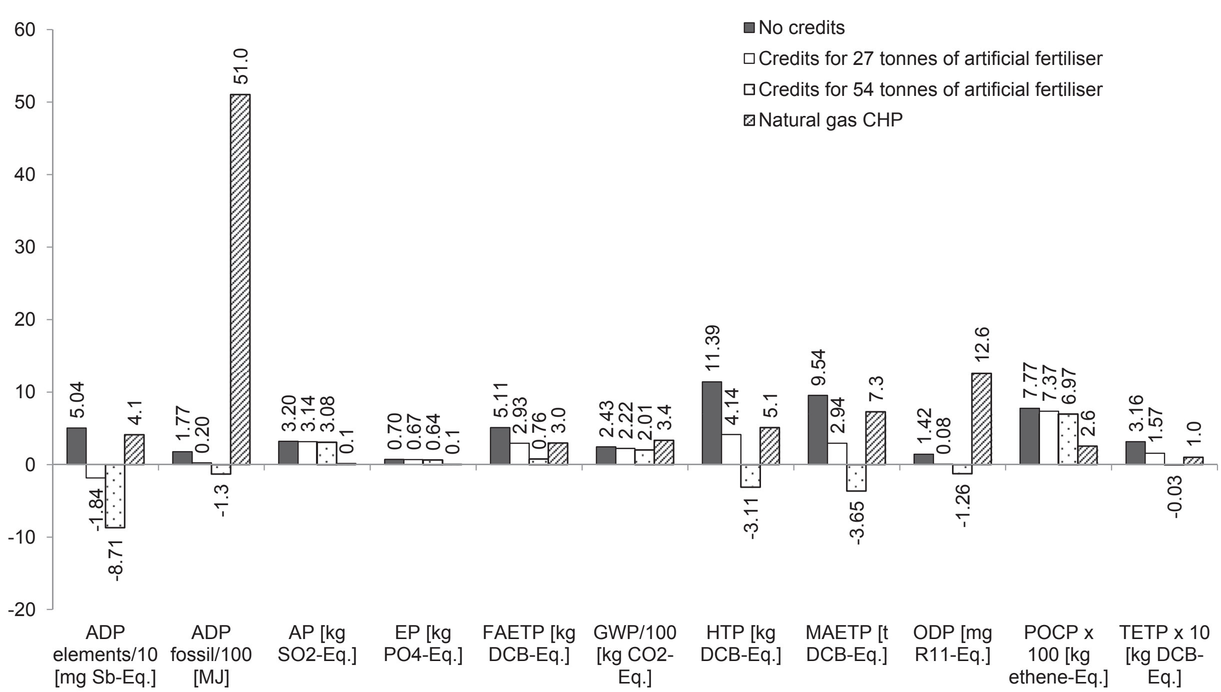

Fig. 11. Effect of system credits for the displacement of artificial fertilisers by digestate. [All impacts per MWh. For impacts nomenclature, see Fig. 4. Some impacts have been scaled to fit and the factors shown against relevant impacts indicate the scaling factor and operation performed during the scaling.]

ammonia [14]. Recovered methane could be combusted in the CHP to recover electricity and heat, converting it in the process to biogenic carbon dioxide. Given that methane from the digestate contributes to 86% of the GWP from the AD-CHP system (see section 3.1), this practice would lead to a significant reduction of this impact. However, it would also lead to the creation of NO_x in the combustion process, increasing the acidification potential.

Another option for storing digestate is natural crust storage. A thick natural crust, formed from the remaining sediment and solids suspended in the liquid, can be created over the digestate, providing a porous surface through which methane is oxidised to CO_2 [34] and can reduce emissions of methane from liquid digestate by 40% [35]. The crust can also reduce ammonia emissions by 66% by reducing volatilisation [36].

The next sections explore possible effects on the environmental impacts of using covered and natural crust storage for digestate.

5.4.1. Covered storage

Covered storage involves installing a sealed tank that can capture up to 80% of methane and ammonia [37,38]. Captured methane is pumped into gas storage to be used in the CHP plant. Manufacture of the tank is considered with the LCA data sourced from Ecoinvent [27].

The results in Fig. 12 show that covering the digestate and using the captured methane in the CHP plant has a mixed effect on the environmental impacts. Large reductions in GWP and POCP occur (80% and 60%, respectively) owing to the avoided methane emissions. There is also an 18% fall in both acidification and eutrophication, owing to the reduction in ammonia emissions. The reduction in these impacts is relatively small compared to the reductions in global warming and photochemical oxidant creation as only around 15% of ammonia emissions are from storage with the rest emitted during digestate spreading on the farmland (see section 2.3).

However, despite the system producing more electricity and heat from the captured methane, all other impacts increase because of the additional raw materials used in the construction of the storage tank, ranging from 36% higher freshwater toxicity to 67% higher ozone layer depletion. Depletion of elements also increases from −18 to 6.7 mg Sb eq./MWh.

Thus, while covered storage reduces some impacts, others are increased substantially. Compared to natural gas CHP, AD-CHP still has 20 and 10 times higher acidification and eutrophication, respectively (Fig. 12). Terrestrial eco-toxicity is now 2.8 times higher while human and freshwater toxicities have gone from being lower than for gas CHP to being 47% and 35% higher, respectively.

5.4.2. Natural crust storage

As mentioned earlier, natural crust storage can reduce methane emissions by 40% through oxidation to CO_2 and ammonia emission by 66% by reducing volatilisation [35,36]. Based on these assumptions, Fig. 12 shows that four impacts can be reduced: global warming by 40%, photochemical oxidant creation by 30% and acidification and eutrophication around 8% each. The other impacts are unaffected.

Therefore, natural crust could present a more sustainable alternative to covered storage, not only environmentally but also economically as a digestate storage tank would add to the investment costs. However, the formation of a natural crust is not guaranteed as it depends upon there being enough fibrous material to float to the top and form a cover. Crust formation can also be hindered by cool climates. In Northern Europe, therefore, an artificial crust may need to be created with, for example, a layer of straw [39]. This would have a similar effect on reducing the emissions, but depending on the type of the artificial cover, it may represent an additional cost to the farmer [38].

5.5. Digestate application

Applying the digestate by scattering on land (known as broadcasting) leads to emissions of ammonia owing to its volatilisation [36]. Post-application emissions from digestate can be avoided through the use of alternative fertiliser spreading techniques such as shallow injection into the soil which can reduce nitrogen loss,

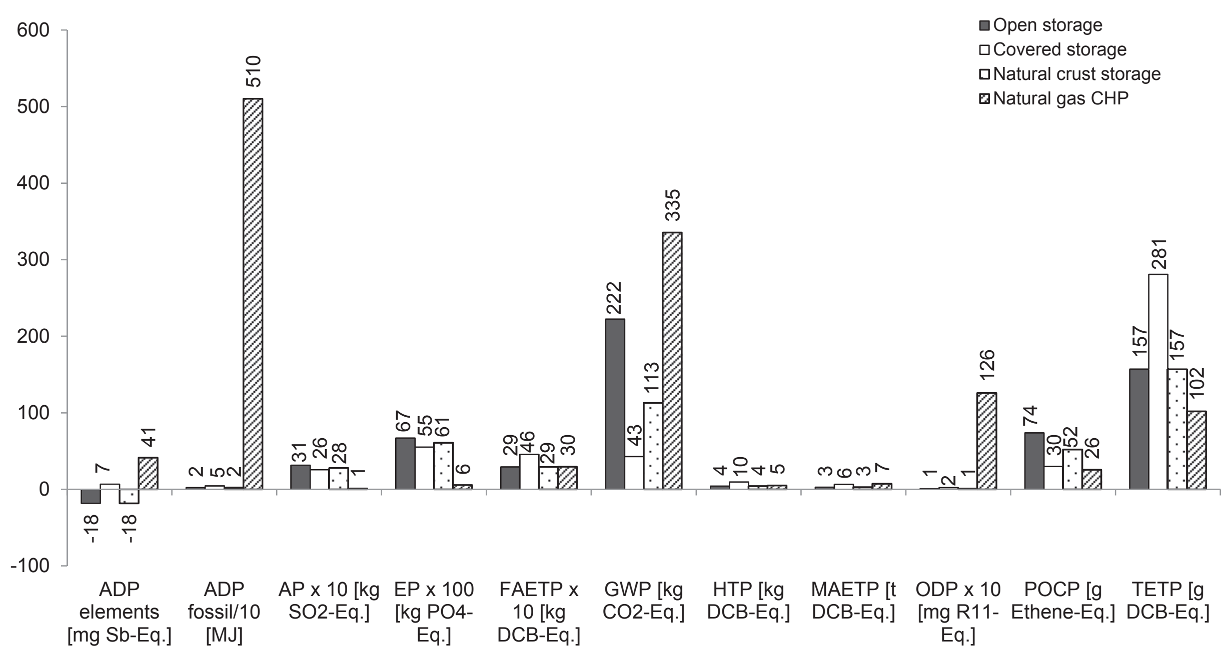

Fig. 12. Effect on environmental impacts of open storage, natural crust storage and covered storage of digestate compared to natural gas CHP. [All impacts per MWh. For impacts nomenclature, see Fig. 4. Some impacts have been scaled to fit and the factors shown against relevant impacts indicate the scaling factor and operation performed during the scaling.]

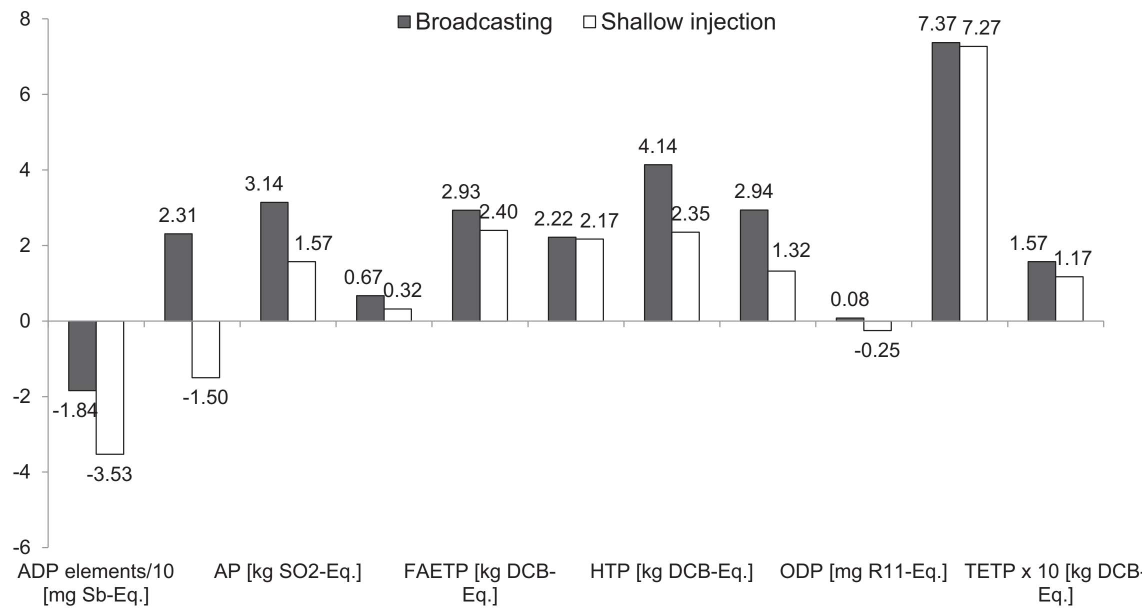

Fig. 13. Effect on the impacts of shallow injection for spreading of digestate on farmland compared to broadcasting. [All impacts per MWh. For impacts nomenclature, see Fig. 4. Some impacts have been scaled to fit and the factors shown against relevant impacts indicate the scaling factor and operation performed during the scaling.]

improving the digestate's nutritional value and further reducing the need for artificial fertilisers [40]. Assuming that similar nitrogen losses occur during digestate broadcasting as during slurry spreading, using shallow injection method can reduce nitrogen loss as ammonia by 60% and displace further 6.6 t/yr of artificial fertilisers[5] [40], in addition to the current 27 t/yr. The environmental impacts estimated based on these assumptions are shown in Fig. 13. The additional energy and equipment required to apply fertiliser by injection method are not considered owing to a lack of data.

As seen in Fig. 13, savings can be achieved in the majority of the impacts, with two impacts becoming negative (depletion of fossil fuels and ozone layer), in addition to depletion of elements. Notably, as a direct result of the reduced ammonia emissions, both acidification and eutrophication are reduced by around 50%. The displacement of artificial fertilisers leads to a similar effect on the impacts as discussed in section 5.3.

Thus, these results indicate that changing digestate application from broadcasting to shallow injection has the potential to reduce most environmental impacts associated with the nitrogen loss. However, injection as a method has its drawbacks. It is energy intensive, slower, more expensive and requires specialised equipment [41]. Also, if the injection is too deep, damage may be caused to the roots of the crop. As these additional energy and equipment requirements were not modelled in this analysis it is not known whether these would cancel out the impact reductions gained through nitrogen retention.

6. Further discussion

The results of this study show that while the AD-CHP system reduces GHG emissions compared to its fossil-fuel alternatives, leachates of ammonia result in much higher acidification and eutrophication. Therefore, the feed-in tariff and renewable heat incentive schemes, currently focussing solely on GHG emissions, may have unintended consequences with regard to these impacts if measures are not taken to prevent ammonia emissions. These are both serious environmental problems which should not be sacrificed in the race to reduce GHG emissions. These impacts could however be avoided or reduced using the techniques discussed in the previous section. Further reductions in acidification could be achieved by adding lime ($Ca(OH)_2$) to the digestate to neutralise the acid emissions [42], although the life cycle impacts of lime would increase some other impacts. Moreover, recirculation of liquid digestate back into the AD tank could help to reduce eutrophication as well as improve biogas yield [43].

It should also be noted that despite the GWP being lower for the AD-CHP system than from fossil fuels, at 222 kg CO_2 eq./MWh it is significantly higher than for alternative bioenergy technologies such as CHP plants using waste woodchip for which the GWP ranges from 10 to 99 kg CO_2 eq./MWh [44]. This is also lower than the GWP estimated for AD in other studies discussed earlier in the paper [17,32]. The sensitivity analysis showed that the GWP is relatively unaffected by the credits for the displacement of artificial fertilisers, reducing only to 201 kg CO_2 eq./MWh with a doubling of fertiliser displacement from 27 t to 54 t. However, the GWP falls into the same range as waste woodchip CHP plants if either covered storage (61 kg CO_2 kg eq./MWh) or natural crust storage (94.6 CO_2 kg eq./MWh) are used to reduce methane emissions from digestate storage.

7. Conclusions

The results of this study indicate that co-generating electricity and heat from biogas produced by anaerobic digestion of agricultural waste can lead to significant reductions in most impacts compared to fossil-fuel alternatives. This includes the global warming potential which can be reduced by up to 50%. However, the acidification and eutrophication potentials are 25 and 12 times higher, respectively, than for the best fossil fuel alternative – natural gas CHP. This is due to the emissions of ammonia during digestate storage and its spreading on land. Furthermore, the photochemical oxidant creation potential is 2.9 times higher

[5] 1.58 kg NH_3/MWh (section 2.3) ⇒ 1.3 kg N/MWh. Artificial fertiliser has 26% N ⇒ 5 kg/MWh of fertiliser. For 2560 MWh/yr ⇒ 12.8 t/yr fertiliser. 85.5% of N escapes (as NH_3) during spreading with 60% of that being saved through the use of injection ⇒ 12.8 t × 0.855 × 0.6 = 6.6 t/yr fertiliser saved.

because of the leakage of methane, also during digestate storage. These impacts can be reduced by using covered storage for digestate and recovering methane for use in CHP as well as through improved techniques for digestate application on farmland. However, even with these measures applied, the acidification and eutrophication potentials remain much higher than for a natural gas CHP (20 and 10 times, respectively). Furthermore, covered storage also causes a substantial increase in some other impacts, particularly human, freshwater and terrestrial toxicity which are all higher than for natural gas CHP. Using natural crust also reduces acidification and eutrophication and does not lead to an increase in other impacts; however, these reductions are still insufficient to make the AD-CHP system a better option than natural gas CHP.

Further savings in the global warming potential can be achieved using high methane-yielding feedstocks, such as waste maize silage. However, if instead of being waste, maize is grown as an energy crop, these savings come at the expense of eight other environmental impacts, all of which increase compared to using waste feedstocks. Thus, there is a danger that continuing the policy of subsidising use of food crops for biogas production will increase other environmental impacts as well as causing competition with food production and related socio-economic consequences.

The impacts are influenced by the amount of artificial fertiliser displaced by the digestate. If no credits are given for the displacement of the fertiliser, then the majority – eight out of 11 – of impacts from the AD-CHP system are higher than from natural gas CHP. However, the GWP is still lower as are the fossil fuel and ozone layer depletion potentials.

Therefore, as the results of this study suggest, three most critical parameters influencing the environmental impacts of bioenergy from AD-CHP systems are feedstock type and source, digestate storage and its application on land. If these can be regulated properly, then the majority of the impacts would be lower than from natural gas CHP. However, even with these measures, acidification and eutrophication are still much higher than for the fossil-fuel alternatives. Both of these impacts cause significant environmental damage and should not be sacrificed while trying to reduce GHG emissions.

Furthermore, although the AD-CHP system has a much lower GWP than fossil-fuel alternatives, it has a higher impact than some other sources of bioenergy, such as CHP plants using waste woodchips. This calls into question the status of biogas as the sole bioenergy option currently eligible for the feed-in tariff scheme in the UK.

Therefore, the findings of this study suggest a clear course of action for policy regarding biogas production. Firstly, the feed-in tariff (FIT) and renewable heat incentive (RHI) schemes should be amended to place further requirements on feedstock type and source to prevent the use of food crops. Secondly, the government should consider providing higher FIT and RHI payments for use of waste as a biogas feedstock relative to other feedstocks. Furthermore, the incentives should be broadened to other bioenergy options in addition to AD, particularly those that use waste as feedstock. Last but not least, regulation should be put in place to require proper digestate handling and spreading on land to prevent emissions of ammonia and related acidification and eutrophication. Otherwise, there is a risk of solving one problem that policy is currently focussing on – climate change – at the expense of other environmental impacts, some of which we have already solved through proper regulation, including acidification.

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