Evaluating cost-effective greenhouse gas abatement by small-scale anaerobic digestion

Funded through an AD Network's Business Interaction Voucher

July 2015

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Acknowledgements

REA and Bangor University would like to thank the following stakeholders for their support and advice:

- Angie Bywater, Methanogen
- Michael Chesshire, Evergreen Gas
- Richard Gueterbock, Clearfleau Limited
- Ollie More, Anaerobic Digestion and Bioresources Association

We would also like to thank AD Network for the funding provided.

EXECUTIVE SUMMARY

This project focuses on the benefits of small scale AD largely based on manures/slurries[1], with particular focus on its GHG emission abatement potential and its cost effectiveness in abating CO_2e emissions when compared with other options.

On-farm AD has significant potential to capture, as a renewable energy source, GHG emissions (e.g. methane) that would be otherwise released by storage and handling of manures and slurries. This means that there are significant GHG savings resulting from anaerobic digestion of manures/slurries due to avoided methane emissions from conventional manure/slurry management and storage. Use of methane from manures/slurries (on their own or in combination with crop feedstocks and residues) not only removes a direct source of GHG emissions, but also displaces the use of fossil fuels in terms of fertiliser and energy production, thus further reducing net GHG emissions.

Small scale, farm AD largely based on manures/slurries is typically less cost-effective in cost per kWh generated than larger scale electricity generation. However, as confirmed by the results shown in this report, since it has the potential to abate substantial amounts of GHG emissions **it is much cheaper when looking at it in terms of carbon savings.** Results show that each tonne of dry matter of cattle slurry avoids 1449 kg CO_2e, and generates 443 kWh of electricity, leading to a **GHG abatement cost of £60 per tonne of CO_2e saved at a FIT rate of £0.20 per kWh**[2]. This compares very favourably with £ 182 per tonne of CO_2e, which is the cost estimated for other renewable electricity generation based on a subsidy level of £0.09 per kWh (previously taken by Government as the maximum level it should pay for renewable energy[3]). **Thus, we conclude that even at a FIT rate of £0.20 per kWh, small scale farm AD largely based on manures/slurries would represent very cost-effective GHG abatement. As highlighted in the Introduction (section 1), there are many other environmental benefits of small scale AD that are not considered in this report but should be recognised by Government when setting subsidy levels to support small scale AD.**

This project shows that **GHG savings as high as 1.8 million tonnes of CO_2e per year could be achieved in the UK if AD were to be deployed across all dairy farms with more than 133 milking cows in the UK. Deploying AD at large dairy farms only would still potentially avoid over 600,000 tonnes of CO_2e per year.** In summary, GHG savings would be considerable and could significantly contribute to meet the UK Carbon Budgets.

In conclusion, small scale, **on-farm AD largely based on manures/slurries can play a significant role in GHG abatement in the future and can deliver this cost effectively**. However, the current FIT regime is inadequate to support an increase in the uptake of smaller scale, AD projects and must therefore be revised to recognise the potential of on farm AD to achieve cost effective carbon reductions and combat climate change.

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[1] AD plants with CHP largely based on manures/slurries would normally be **<** 100kW electrical capacity.

[2] This FIT rate is an illustrative figure which corresponds to the level that, based on industry suggestions, would be required to make small scale AD (< 100 kWe) financially viable.

[3] See section 5.6 in Appendix 2 for a more detailed explanation on the reason why this benchmark value has been considered. This report does not consider the impact of the Budget announcement (8 July) on removing the exemption to the Climate Change Levy for renewable electricity as the analysis was conducted before then. For comparison purposes, it seems a reasonable working assumption that the impact of this would be felt equally across different technologies.

1. INTRODUCTION

This work, funded by the BBSRC AD Network, is specifically focused on carbon savings and abatement costs associated with a plausible range of farm based AD scenarios, using primarily livestock slurries.

Although this study primarily focuses on the slurry/manure, small scale AD model, it is important to recognise that small AD plants can handle a range of feedstocks, not only on farms (manure and other residues) but also community projects (local waste arisings) and on commercial sites (handling production residues and wastewaters). REA is very supportive and would like to see increased deployment of multiple 'on-site' small scale AD plants as these, amongst other numerous benefits:

- can handle residues at the place where they are produced and facilitate local energy supply
- have the ability to handle materials generated in their immediate locality
- generate growth and jobs

This work primarily focuses on GHG mitigation, however it is worth pointing out that there are numerous additional benefits associated with farm AD, all of which have been already extensively documented. These include improved slurry handling, reduced water/air pollution, replacement of manufactured fertilisers, nutrient and organic matter recycling and a significant reduction in the farm carbon footprint. See, for example, the RASE report, and REA's paper "Smaller Scale UK Biogas Producers: Problems & Solutions" for more detail.

Over 90 million tonnes of manures and slurries are generated each year[4] in the UK, but only 636,000 tonnes are currently treated through AD (NNFCC, 2015). On-farm AD has significant potential to capture, as a renewable energy source, GHG emissions (e.g. methane) that would be otherwise released by storage and handling of manures and slurries. This means that there are significant GHG savings resulting from anaerobic digestion of manures/slurries due to avoided methane emissions from conventional manure/slurry management and storage. Use of methane from manures/slurries (on their own or in combination with crop feedstocks and residues) not only removes a direct source of GHG emissions, but also displaces the use of fossil fuels in terms of fertiliser and energy production, thus further reducing net GHG emissions.

LCA modelling of AD and bioenergy scenarios in Defra project AC0410 presented default GHG abatement effects and costs for a limited number of plausible, farm based AD scenarios, and presented ranges around those values based on sensitivity analyses. Abatement costs were calculated on the estimated "break-even" cost[5] for farmers introducing AD, using the *LCAD* tool. In this project, we applied a slightly modified LCA framework with modified subsidy-related abatement cost calculations, with updated manure and digestate management practice parameters based on Defra survey data, in order to determine the most likely range of GHG abatement costs associated with small scale AD.

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[4] Source: Anaerobic Digestion Strategy and Action Plan, 2011

[5] The difference in annual farm revenue before and after the introduction of an AD plant to a farm system, in the absence of any AD-subsidy support.

We evaluated a number of relevant small scale scenarios in addition to those considered in project AC04010. We have done this by using an updated *LCAD EcoScreen* tool developed during a subsequent KESS project. This tool calculates environmental credits and burdens for one tonne of dry matter feedstock, and user-defined combinations of feedstock mixes, based on selection of key counterfactual and AD operational parameters identified in Defra project AC0410 (elaborated in more detail later).

Abatement costs were calculated based on a subsidy level of £0.20 per kWh, as based on industry suggestions this is the level that would be required to make small scale AD < 100 kWe financially viable. However sensitivity analyses were undertaken in relation to different illustrative levels of feed-in-tariff for small-scale AD electricity generation between £0.16 and £0.20 per kWh.

In addition, this abatement cost is based on the assumption that grid average electricity is replaced. Sensitivity analyses were undertaken in relation to different types of replaced grid electricity generation (natural gas combined cycle marginal grid electricity; coal base load electricity; national grid mix electricity). As expected, when coal base load electricity is replaced, GHG abatement costs are even lower. This assumption may be more appropriate in the case of technologies such AD which provide reliable base-load power.

In addition, a range of co-digestion scenarios was explored at different inclusion rates, for grass and maize, with sensitivity analyses around crop-biogas yields. Finally, results were extrapolated to national GHG abatement potentials, based on scenarios of deployment dependent on minimum farm size thresholds for economic viability, using DairyCo structural data on the dairy sector.

All results of all sensitivity analyses undertaken in this study can be found in Appendix 2.

2. RESULTS

2.1 Slurry only

The abatement cost per tonne of CO_2e avoided for the national average farm AD scenario resulting from this study is **£ 60/tonne of CO_2e avoided**. This is based on a subsidy level of 0.20 / kWh, which is an illustrative FIT rate and, based on industry suggestions, is that level that would be required to make small scale AD < 100 kWh financially viable. In addition, this result is based on replacement of grid average electricity generation.

Sensitivity analyses across a range of FIT rates (between £ 0.16 and 0.20 / kWh) were undertaken and are shown in Appendix 2. Sensitivity analyses were also undertaken in relation to different types of replaced grid electricity generation (natural gas combined cycle marginal grid electricity; coal base load electricity; national grid mix electricity). As expected, abatement costs are even lower when it is assumed that coal base load electricity is replaced. This may be more appropriate since technologies such as AD provide baseload, reliable electricity.

As shown below, the main process affecting GHG abatement is the avoidance through AD of GHG emissions that would otherwise be released from traditional manure/slurry management systems ("avoided manure storage and application") – including storage, transport and spreading of manures.

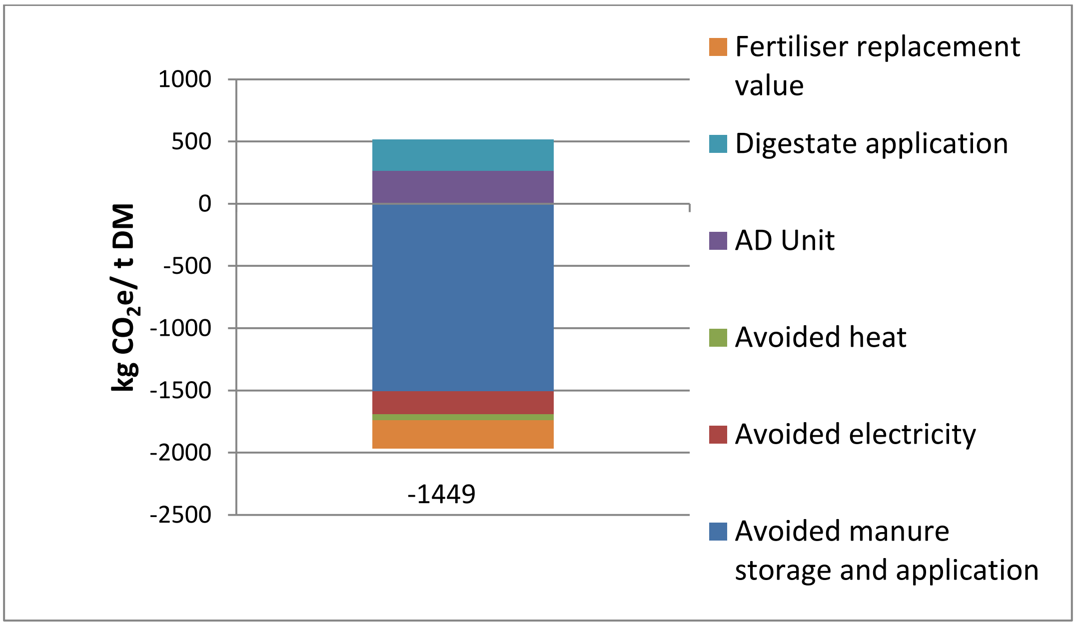

Figure 1. Contribution of different processes to changes in GHG emissions for one tonne of dry matter dairy slurry

The GHG abatement costs presented above are benchmarked against the GHG abatement cost for off-shore wind electricity generation, based on a conservative subsidy of £0.09 per kWh, which is a reasonable proxy for the subsidy level for offshore wind in 2016 under the RO and has been previously used as a benchmark for the maximum amount that Government is willing to pay to support renewable energy[6]. The costs in the chart assume that GHG abatement approximates to avoided GHG emissions from grid electricity generation. As highlighted above, it is important to note that biogas is one of the most versatile renewables the UK has at its disposal, providing reliable base-load power, and helping to balance the variability of other renewables. Unlike some other renewable technologies, energy produced from AD can be either continuous, not dependent on changeable weather conditions or used to meet peaking demand from consumers.

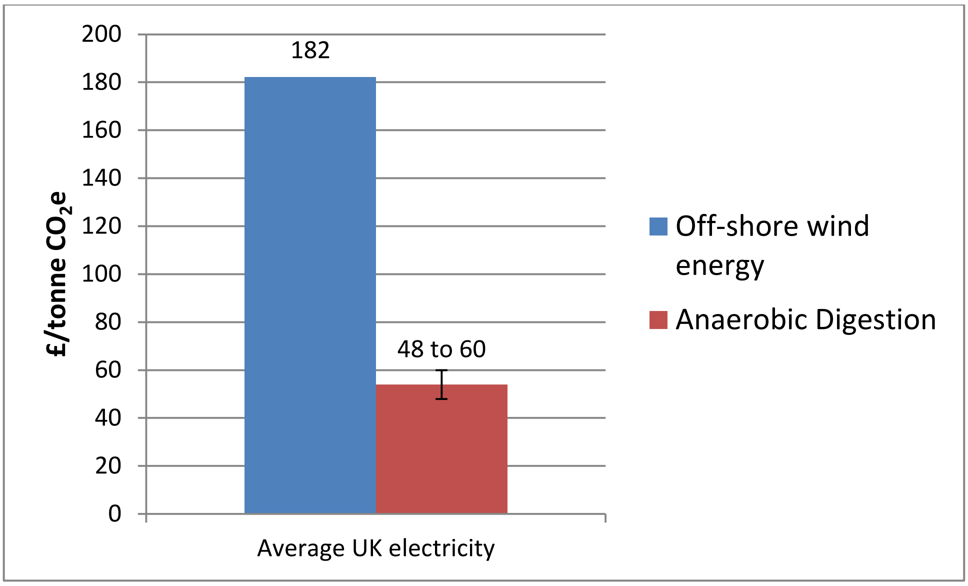

Figure 2. Comparison of abatement costs for off shore wind renewable energy and AD based on replacement of grid average electricity generation. The Error bars show the range of values for lower and higher FIT rates (0.16 and 0.20 £/kWh, respectively).

3.3 Co-digestion scenarios

Manures and slurries produced on farm are a good candidate for anaerobic digestion, but their relatively low energy yield means that it may be beneficial to co-digest them with energy rich material. Food wastes would represent a useful opportunity but complications in terms of permitting and safe handling present barriers for small scale on-farm use. The concept of hub and pod AD can make this more viable and a recent report procured by WRAP has been looking at how the model can help drive innovation in AD development generally in the UK.

Sustainably grown crop feedstocks can be beneficial in the feedstock mix both to increase gas yields and to improve the yields of other crops in rotation. These are termed ‘break crops’.

The following charts show that GHG abatement costs rise with inclusion of co-digested crops but GHG savings are still lower or comparable with offshore wind at up to 40% inclusion (dry matter basis).[7]

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[6] See a detailed explanation of this point in the Methods section of this report

[7] Assuming the enhanced FIT generation tariff is paid on generation from all the biogas produced

Both maize and grass co-digestion scenarios achieve similar GHG abatement costs. Possible ILUC emissions are excluded.

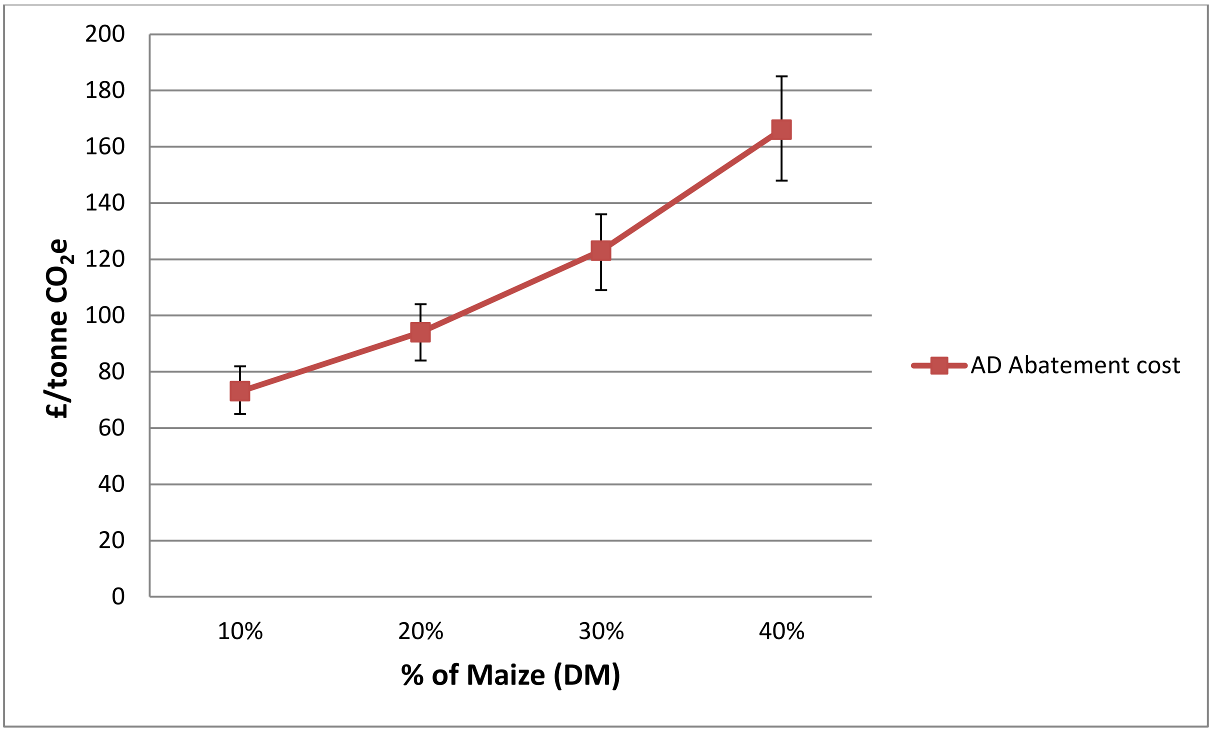

Figure 3. Abatement costs for cattle slurry with increasing proportions of co-digested maize. Error bars show the range of values for lower and higher FIT rates (0.16 and 0.20 £/kWh, respectively).

3.7 Potential UK GHG savings from on-farm AD

Work done by the RASE and AEA Group[8] indicates that for the greatest impact, low cost AD plant should be targeted at dairy farms, starting from about 100 cows and upwards, since anaerobic digestion can improve handling of livestock slurries/manures generated at dairy farms and consequently significantly reduce emissions, as well as harness the renewable energy potential.

In this section we have estimated the overall GHG savings that could be achieved in the UK if AD is deployed across:

1) all dairy farms in the UK with more than 133 milking cows;
2) all dairy farms in the UK with more than 267 milking cows; and
3) all dairy farms in the UK with more than 400 milking cows.

These estimates are based on the annual UK milk production of 15 billion litres (DairyCo, 2013), a dry matter excretion rate of 0.256 kg per L milk produced (Styles et al., 2014), and on the GHG abatement results obtained per tonne DM of cattle slurry for the average AD national scenario (1449 kg CO_2e/t DM).

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[8] Bringing small scale AD to UK farmers – the challenge; Paper presented by Prab Mistry (AEA Group) & Ian Smith (RASE) at the European Bioenergy Expo and Conference; Stoneleigh Park, Warwickshire, UK; 6 - 7th October, 2010.

Scenario 1: AD is implemented across all dairy farms with more than 133 milking cows

66% of 15 billion litre milk*0.128 kg DM[9] slurry stored per L milk (50% time outdoors) = 1,267,200 tonnes DM cattle slurry/year.

Total CO_2e abatement = **1,836,488** t CO_2e/year.

Scenario 2: AD is implemented across all dairy farms with more than 267 milking cows

AD is implemented across all dairy farms with more than 267 milking cows: 31% of 15 billion L milk * 0.128 kg DM slurry per L milk (50% time outdoors) = 595,200 tonnes DM cattle slurry/year.

Total CO_2e abatement = **862,665** t CO_2e/year.

Scenario 3: AD is implemented across all dairy farms with more than 400 milking cows

These farms represent an estimated 25% milk produced on “large” dairy farms specified by DairyCo (2013): 25% * 31% * 15 billion L milk * 0.2304 kg DM slurry per L milk (90% time indoors)= 267,840 tonnes DM cattle slurry.

Total CO_2e abatement = **388,100** t CO_2e/year.

Scenario 3.1: Alternatively, if all the very large dairy farms are assumed to use mainly lagoon slurry storage, then total CO_2e abatement could equal 573,615 t CO_2e/year.

The results are summarised in table 1 below.

Table 1. Potential UK GHG savings from on-farm AD under different scenarios

Scenarios	GHG abatement (t CO_2e/year)
Scenario 1	1,836,488
Scenario 2	862,665
Scenario 3 / 3.1	388,100 / 573,615

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[9] Half of the 0.256 kg per L milk produced (Styles et al. (2014))

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4. APPENDIX 1: METHODS

Introducing small-scale AD to farm systems leads to the avoidance of GHG emissions (credits) and the generation of new GHG emissions (burdens), as indicated in Figure . Credits include avoided electricity generation, avoided fossil-fuel heating, avoided manure management and avoided fertiliser manufacture and application. Burdens include CH_4 and NH_3 emissions from fermenter leakage, digestate storage and field application. The *LCAD EcoScreen* tool applies consequential life cycle assessment (CLCA) to evaluate the net change in GHG emissions associated with the digestion of one tonne of dry matter feedstock under user-defined settings reflecting important counterfactual and AD operational factors. This study evaluated the net change in direct and indirect GHG emissions associated with digestion of dairy slurry, including scenarios with limited co-digestion of crops. Dairy farms in the UK provide large quantities of cattle slurry which are suitable for AD but have low energy potential, therefore in most cases it is beneficial to include higher biogas yielding feedstocks (e.g. maize silage, grass silage, etc...) to enable slurries to be used economically in AD.

Important considerations and assumptions are summarized below.

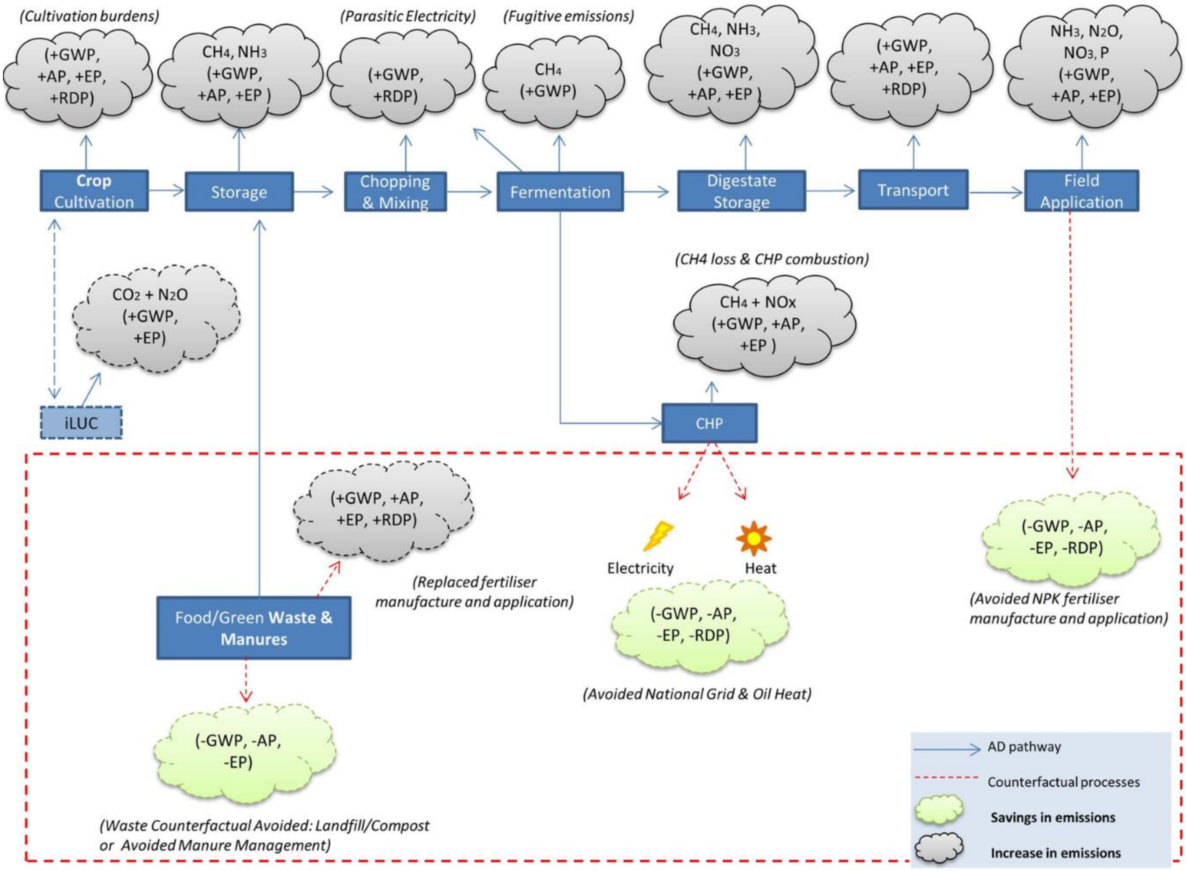

Figure 4.1 Major processes and emissions considered in the *LCAD EcoScreen* Tool

4.1 Feedstock characteristics

Table 5.1 below summarises feedstock characteristics applied in the *LCAD EcoScreen* tool, including nutrient composition (which affects fertiliser replacement value of the digestate and ammonia emissions) and biomethane yields (FNR, 2010)[10]. For co-digestion scenarios, GHG emissions associated with feedstock cultivation were taken from Styles et al. (2015), based on UK yield and fertiliser application statistics.

Table 4.1. Feedstock characteristics applied in the *LCAD Eco Screen tool* (Defra 2014a)

FEEDSTOCK						DIGESTATE
Type of feedstock	**Dry matter**	**Total N**	**P_2O_5**	**K_2O**	**Methane Yield**	**NH_4-N in digestate**
	%	kg/m3 DM	kg/t DM	kg/t DM	m^3 CH_4/t DM	% TN
Cattle slurry	10	41	18	40	140	75
Maize silage	30	14.1	4.6	14.6	337	37
Grass silage	25	16.8	6.8	24	280	37

4.2 Avoided manure management emissions

Methane emission factors from different kinds of manure storage system were calculated using equations 10.23 and 10.24 of IPCC (2006), including methane conversion factors of 0.11, 0.17 and 0.67 were applied for crusted tanks, open tanks and lagoons, respectively. The UK fertiliser manual RB209 (Defra 2010) provides values for manure total nitrogen (TN) content of manures after storage. Adding ammonia-N losses during storage (Misselbrook et al. 2012) indicates total nitrogen (TN) values before storage, which also reflects the TN input to AD plants. Ammonia emissions contribute to indirect N_2O emissions, and are calculated as percentages of total ammonium N (TAN) in the digestate based on factors for different storage systems: 52%, 10% and 5% for lagoon, tank without crust and tank with crust, respectively (Misselbrook et al. 2012).

Broadcast application remains the most common method of slurry application in the UK. NH_3 and NO_3 emissions, and fertiliser replacement value, for broadcast application of manure in the baseline situation (prior to AD implementation) were calculated using factors derived in MANNER-NPK (Nicholson et al. 2013), as a mean of March and September application. Direct and indirect soil N_2O emissions were based on IPCC (2006), and an emission credits for fertiliser replacement were calculated based on avoided fertiliser manufacture emissions (Ecoinvent, 2010), and avoided field

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[10] The biomethane yield values for grass and maize in the table are quite conservative, based on feedback from industry, however higher biomethane yield values are covered by the sensitivity analyses summarised in the appendix 2.

emissions of N_2O, NH_3 and NO associated with fertiliser application (IPCC, 2006; Misselbrook et al. 2012).

4.3 Electricity and heat generation

Biogas yields depend on feedstock type and the presence of a secondary fermenter. In the first instance, a fraction of methane is lost from the digester, before entering the CHP unit (2.5%, Table 4.2). Further methane may be lost during storage of the digestate in unsealed tanks/lagoons (Table 4.2). For biogas reaching the CHP generator, a conversion efficiency of 37.5% (Defra, 2014) was assumed for electricity generation in small-scale CHP plants, with 10% of gross electricity output used as parasitic load for plant operations. Net CHP electricity output is assumed to replace marginal grid electricity, generated by natural gas combined cycle turbine power stations (DECC, 2014), with the associated GHG credit calculated based on the appropriate GHG emission factor from the Ecoinvent (2010) database. A sensitivity analysis was performed based on GHG emission factors for the average grid mix and coal based load generation, using data from Defra (2015).

Table 4.2 Methane leakage rates form the fermenter and digestate stores

Storage infrastructure type	Lagoon	Unsealed tank	Sealed tank/secondary fermenter
Storage loss CH_4 (% produced)	10	5	2.5
CH_4 loss in CHP (%)	0.5	0.5	0.5

The CHP generator converts 42% of the biogas lower heating value into useable heat, 20% of which is used to heat the fermenter. On a large dairy farm 25% CHP heat output is likely to be used for farm operations (Defra, 2014a). Therefore, 25% of CHP heat output was assumed to replace oil-heating, avoiding oil-heat environmental burdens quantified in Ecoinvent (2010).

4.4 Digestate storage and application

Digestate storage gives rise to methane and ammonia emissions. Methane loss rates were expressed as a fraction of total methane generated, over the entire digestion and digestate storage process, based on data from Jungbluth et al. (2007), as shown in . Ammonia emissions were calculated as a percentage of TAN based on emission factors for different storage systems used by Misselbrook et al. (2012) for national ammonia inventory reporting: i.e. 10% and 52% for open tanks and open lagoons, respectively.

Emission coefficients for ammonia and nitrate emissions, and fertiliser-nutrient replacement, associated with field application of digestate were calculated using MANNER NPK (Nicholson et al., 2013), as for counterfactual manure management except that it was assumed a trailing hose was used for digestate application. Emission coefficients were derived in relation to residual TAN in the digestate, after accounting for storage losses.

4.5 Weighted mean calculations

Multiple runs of the LCAD *EcoScreen* tool were made for various permutations of counterfactual manure storage and digestate storage. Primary results are presented for a weighted mean mix of these permutations, representing the expected average outcome for small-scale AD implemented on UK dairy farms. Based on farm practise statistics (Defra, 2014b), counterfactual (baseline) slurry storage on dairy farms was apportioned to crusted tanks or lagoons, open tanks and open lagoons in the following ratios: 0.15, 0.3 and 0.52. Where dairy farms introduce an AD plant, it is assumed that digestate storage occupies the same infrastructure as previously used for manure storage ().

Table 4.3. Prevalence of counterfactual manure storage and digestate storage used to calculate a weighted-mean AD GHG abatement effect

Counterfactual manure storage (Defra, 2014b)	Digestate storage (assumption)	Contribution ratio to the weighted mean national scenario (Defra, 2014b)
Crusted tank	Open tank	15%
Open tank	Open tank	32%
Lagoon	Lagoon	53%

It was assumed that digestion of manures did not lead to any additional transport compared with the baseline situation. For crop co-digestion scenarios, it was assumed that crop feedstock and digestate were transported 10 km from/to fields, with emission factors applied on a tkm basis from Ecoinvent (2010). 10 km represents a conservative average based on existing crop AD units. In a small-scale dairy AD situation, the transport distance could be less, but in any case this is not considered to affect significantly the GHG balance.

4.6 GHG abatement costs: benchmark values and comparison with other financial incentives

It is not completely straightforward to compare Government support between policies – not only are the policies structured in different ways, but the technologies themselves have different strengths and weaknesses.

The coalition Government consistently took the support levels offered to offshore wind under the Renewables Obligation as the maximum government should pay, treating it as the ‘marginal’ technology to meet the 2020 renewables target. That was previously set at 2 ROCs/MWh, falling to 1.9 from 1 April 2016 and 1.8 a year later. AD in the RO receives the same level, and this was also the starting point for AD 500kWe and above in the Feed in Tariff. Although the precise value is uncertain due to commercial arrangements around ROCs and degression mechanisms in the feed in tariff, 9p/kWh seems like a reasonable reference point.

5. APPENDIX 2: Sensitivity analyses: tables and charts

Slurry only scenario

Table 5.1. Abatement costs based on GHG avoidance and electricity exported for a national average farm AD scenario across different FIT rates (natural gas electricity).

Electricity generation replaced	**GHG emissions avoided by AD**	**Calculated electricity exported**	**Abatement cost at an assumed FIT rate of £0.16/kWh**	**Abatement cost at an assumed FIT rate of £0.18/kWh**	**Abatement cost at an assumed FIT rate of £0.20/kWh**
	kg CO_2e/tonne DM	**kWh/yr**	**£ per tonne CO_2e**	**£ per tonne CO_2e**	**£ per tonne CO_2e**
Natural gas	-1449	443	49	55	61
Grid average			48	54	60
Coal			43	48	54

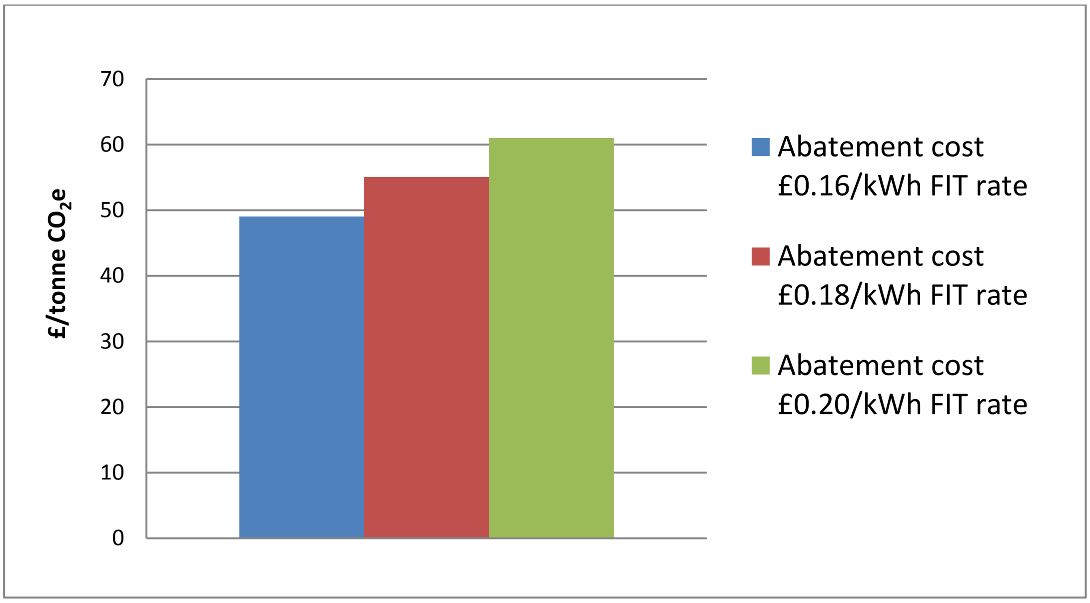

Figure 5.1. Abatement costs for dairy slurry digestion across different FIT rates which represent possible ranges of subsidies required to make technologies financially viable (natural gas electricity substitution)

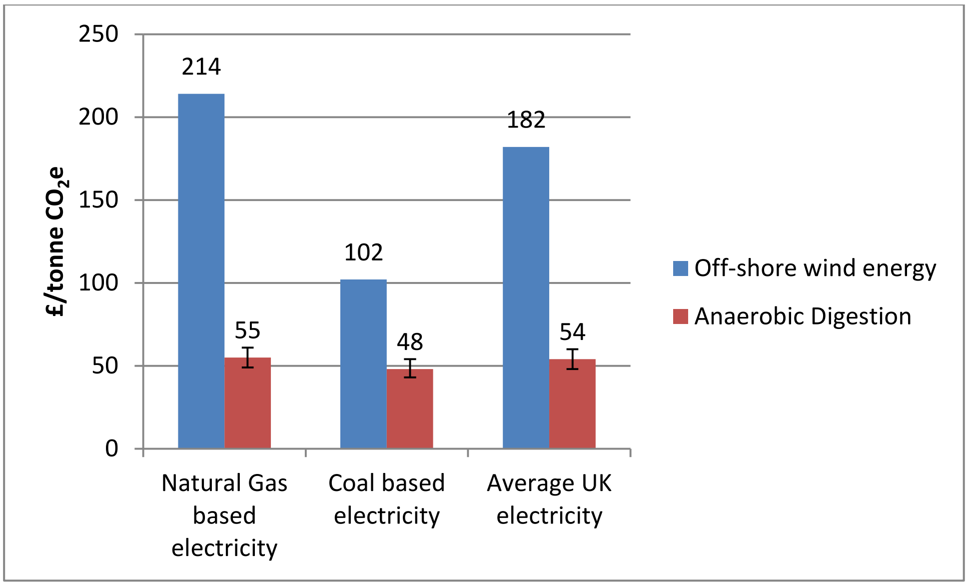

Figure 5.2. Comparison of abatement costs for wind renewable energy and AD for different electricity generation assumptions, at a FIT rate of £0.18 per kWh. Error bars show the range of values for lower and higher FIT rates (0.16 and 0.20 £/kWh, respectively).

Co-digestion scenarios

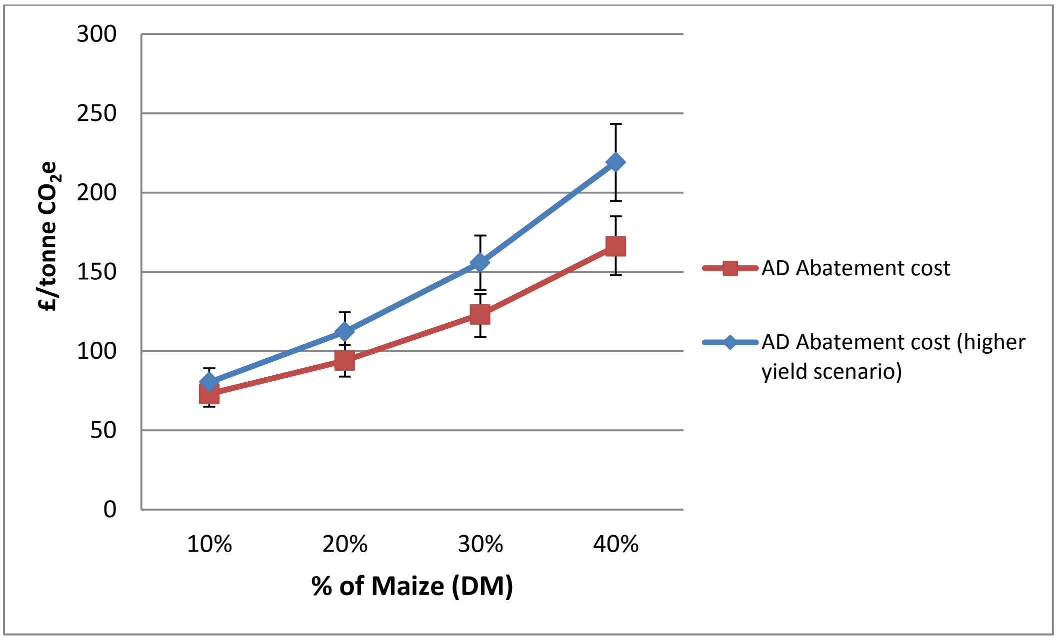

Figure 5.3. Abatement costs for cattle slurry with increasing proportions of co-digested maize, at standard and +50% maize biogas yields. Error bars show the range of values for lower and higher FIT rates (0.16 and 0.20 £/kWh, respectively).

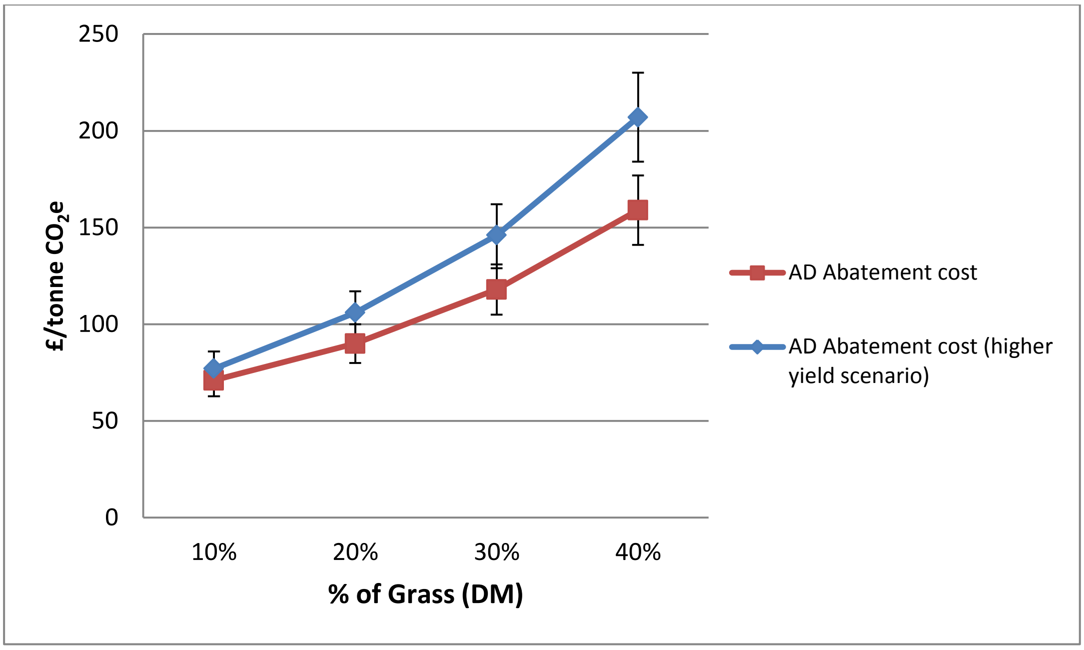

Figure 5.3 Abatement costs for cattle slurry with increasing proportions of co-digested grass, at standard and +50% grass biogas yields. Error bars show the range of values for lower and higher FIT rates (0.16 and 0.20 £/kWh, respectively).