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Expanding biogas on UK dairy farms: a question of scale

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Abstract

Expanding Anaerobic Digestion (AD) in the UK will not only depend upon finding appropriate economic structures to support on-farm developments but also an appreciation of environmental issues such as less Greenhouse Gas (GHG) emissions; reduced use of artificial fertilisers; and better management of farm wastes. At the core of this paper is the Anaerobic Digestion Analytical Model (ADAM) that examines the economic and environmental impacts of integrating AD into UK farming systems. However, the average dairy farm in the UK is not of sufficient size to enable profitable biogas production. Indeed, farm size, as represented by FBS/FAS data used in ADAM, needs to be scaled by three to four times for a biogas enterprise to break-even. To boost profitability, some farms may use additional energy (food and non food) crops as well as other high energy sources such as biodiesel residues etc. In some circumstances, possibilities may exist for neighbouring farmers to co-operate and manage a biogas installation that processes manures and energy crops to increase the scale of an on-farm plant. Despite issues of scale however, on-farm AD plants do have the capacity to (i) reduce Carbon Dioxide equivalent (CO_{2e}) emissions that a dairy farm produces; and (ii) the by-product of digestate provides farms with greater nutrient availability for crops.

Keywords: Anaerobic digestion; biogas; dairy farming; carbon dioxide, nutrients, digestate

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1. Introduction and background to research

Anaerobic digestion (AD) is the process that digests organic material to produce biogas (60-80% methane) and digestate. There are several environmental benefits associated with AD that include the production of green energy; reduced Greenhouse gases (GHGs) emissions; a digestate that can substitute artificial fertilisers; and improved water quality from better management of farm wastes. The UK policy context of expanding heat and energy production from anaerobic digestion formed part of a cross Defra project - Farming for the Future programme - which also contributed to the former Government's climate change programme, waste strategy, biomass strategy and the food chain programme. Some of the main drivers were outlined in the Biomass strategy that aimed to "*maximise the potential of biomass to contribute to the delivery of our climate change and energy policy goals: to reduce CO_2 emissions, and achieve a secure, competitive and affordable supply of fuel*" (Defra 2007b). Putting this in the context of the EU's policy framework, for some years, EU policy on renewable energy has been devolving and the 'Climate Change Package' commits Europe to transforming itself into a highly energy-efficient, low carbon economy (European Commission 2010b). By 2020 the EU is committed to reducing greenhouse gas emissions by at least 20% below 1990 levels; ensuring that 20% of EU energy consumption comes from renewable resources; and a 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency.[1] Other EU drivers that influenced UK policy include the landfill directive (1999/31/EC), which came into force in 1999 with the intention of preventing or reducing adverse effects of landfill waste on the environment; and the Water Framework Directive (2000/60/EC) (European Commission 2010). It is against these policies that this paper assesses the potential of integration of AD into UK dairy systems at the farm scale, including an assessment of `spin-off` benefits to nutrient cycling. Furthermore, it provides an environmental economic analysis of the costs and benefits associated with biogas production and reduced carbon dioxide equivalent (CO_{2e}) emissions.

2. Methods

At the core of this paper is the Anaerobic Digestion Analytical Model (ADAM), a complex spreadsheet model, which examines the economic and environmental impacts of integrating AD into UK farming systems.[2] Figure 1 schematically illustrates three subsections of ADAM: farming systems, anaerobic digestion process, and import/export markets.[3] This arrangement enables the integration of AD into dairy and pig agricultural systems at the farm scale but also enables the appraisal of much larger scale AD plants both in on-farm and off-farm locations in terms of their economic viability, and nutrient recycling back to agricultural land, and carbon saving potential. With ADAM's genesis in Defra project CTB 0301 and RELU project RES 224-25-0086 (Butler and

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[1] These are also known as the 20-20-20 targets.

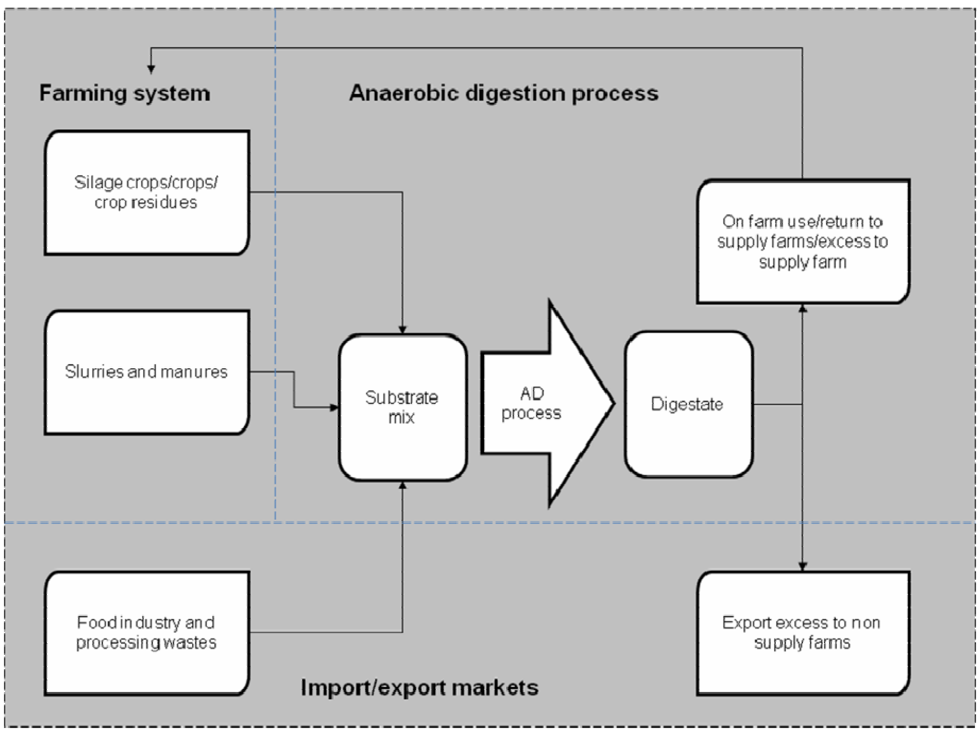
[2] The research explored in this paper is based on a recently concluded Defra Project (AC0406), the optimisation and impacts of expanding biogas production in the UK. This project was a collaboration between North Wyke Research (Formerly IGER and project leader) and the Centre for Rural Policy Research at the University of Exeter.

[3] For brevity, this third section is not discussed in this paper.

Turner 2007, Chadwick et al. 2008, Butler et al. 2008), in this paper ADAM assesses the integration of AD into dairy systems at the farm scale.[4] Deriving cost data from the Farm Business Surveys for England, Wales and Northern Ireland, and the Farm Accounts Survey in Scotland ensures UK coverage and reflects different regional cost structures.[5]

The following sections detail the most important assumptions and relationships of ADAM, which particularly focus on those for dairy farming. Included are the inputs that are fed into the AD process, the AD process itself and the calculations to transform the substrates in to energy, the synergies and substitutive effects of digestate with artificial fertilisers, some comments on establishing the capital cost of AD plants, and the accountancy of carbon.

Figure 1: *Schematic diagram of ADAM*



2.1 Inputs in to AD (substrates)

Linking farming systems to AD plants are inputs into the AD process known as substrates. ADAM explicitly models farm substrates including pig and dairy slurry; grass and maize silage (although these could also be imported on to the farm); and imported substrates of poultry manure, potato waste, food wastes (kitchen wastes) and meat and bone waste from slaughterhouses. Since this paper focuses on dairy farming in the UK, these substrates are restricted to dairy slurry, and grass and maize silage. In Europe, grassland biomass is an established feedstock for biogas production

[4] Defra project CTB0301: New Integrated Dairy Production Systems: Specification, Practical Feasibility and Ways of Implementation; and RELU project RES 224-25-0086: Sustainable and Holistic Food Chains for Recycling Livestock Waste to Land.

[5] For compatibility purposes, all cost data was representative for 2008.

and surveys from Germany and Austria have shown that grass is used in over 50% of AD plants and is the second most common feedstock after maize (Hopfner-Sixt and Amon, 2007; Weiland, 2006, cited in Prochnow et al. 2009). While maize, as an energy crop, produces high biogas yields, its growth favours warmer climates and tends to be limited to lowland parts of southern and central England and coastal Wales, although the crop is grown commercially on a small scale in some parts of northern England and Scotland (Lister and Subak undated). Therefore, using grass silage as the main energy crop substrate in ADAM acknowledges that not all areas in the UK with dairy farms necessarily produce maize silage.

The advantage of using these substrates from the large number of possibilities partly reflects dairy farming systems in the UK, and partly the fullness of the data available regarding dry matter (DM), organic dry matter (oDM), biogas potential of organic total solids (oTS) and the Nitrogen (N) and Phosphorus (P) contents within these substrates. Derived from Defra's guides to managing livestock manures (Defra 2001) and fertiliser recommendations (RB209) (Defra 2000), Table 1 details the ranges of the coefficients that are used in ADAM for this paper.

2.2 Processes of AD

In assessing the quantity of biogas produced, volatile solids (VS), which is the organic matter content of a substrate that can be converted into biogas, is calculated by multiplying total DM of a substrate multiplied by its oDM content. For example, if the DM content of dairy slurry is 21.9 tonnes per day and its oDM content is 75%, total VS will be 16.4 tonnes. Therefore, the biogas yield from this per kg of VS would be approximately, 7m^3 per day assuming that each kg of VS releases 0.45 m^3 of biogas. However, there are many parameters that influence the release of biogas during the methane fermentation phases[6] such the consistency of temperatures, correct pH value and Carbon-to-Nitrogen (C:N) ratio, and DM content for example (Deublein and Steinhauser 2008, EU-AGRO-BIOGAS 2008).

Table 1: *Range in values assumed for DM, oDM and N and P in substrates*

Substrate	**Dry matter (DM)** (%)	**Organic dry matter (oDM)** (%)	**Biogas yield** m^3/(kg VS d^{-1})	**Nitrogen content** (kg/tonne)	**Phosphorus content** (kg/tonne)
Dairy Slurry	0.06 - 0.11	0.65 - 0.85	0.1 - 0.8	3.0 – 4.25	1.2 – 1.7
Grass Silage	0.21 - 0.4	0.76 - 0.9	0.6 - 0.7	4.88 – 8.54	3.8
Maize Silage	0.2 - 0.4	0.94 - 0.97	0.6 - 0.7	4.08	2.6

Sources: Defra (2000), Defra (2001) and Deublein and Steinhauser (2008).

The AD process generates electricity and heat as well as digestate after the extraction of the biogas. ADAM assumes that an AD plant is operational for 95% of a year (8,322 hours). From this, the plant itself uses 8% of the electricity with the remainder sold in to the national grid. Calculating the output in terms of per kWh of electricity (kWh_e) uses a formula similar to that of Anderson (2010). In the UK, the calorific value of 1m^3 natural gas in the national grid is 39MJ (Pöyry Energy Consulting 2009). This value equates to 10.8kWh of potential energy. In biogas, approximately 60% is methane although this depends on the type of substrate being used, giving a potential of 6.5kWh of energy. However, the Combined Heat and Power (CHP) unit determines the level of electrical and heat

[6] Methane fermentation phases include hydrolysis, acidogenesis, acetogenesis and methanation (Weiland 2010).

energy produced and the scale of energy losses that occurs. According to manufacturers' data, electrical efficiency may vary between about 30% and 40% whereas for heat efficiency this is higher at 50%. As such, $1m^3$ of biogas can produce between $1.9kWh_e$ and $2.6kWh_e$ (and 3.3kWh of heat). Replicating the Anderson (2010) methodology and calibrating ADAM using specially commissioned manufacturer's data, sets electrical efficiency for the CHP at 33%.[7]

2.3 Digestate and farm fertiliser use

From the process of AD, a nutrient rich material called digestate provides a bio-fertiliser and soil conditioner for use on farms. While digestate provides some additional nutrients over and above slurry, the expected use of artificial fertiliser may still be necessary. ADAM accounts for the 'nutrient economy' (i.e. crop requirements vis-á-vis available nutrients) for Nitrogen (N) and Phosphorus (P) and the impact that excesses in these are likely to have on farming systems in the UK. Potassium (K) on the other hand is not considered since, unlike N and P, K is not known to cause adverse direct or indirect environmental effects and economically, as a resource there are large reserves (Johnston 2005). While K is not reported, any savings in K fertiliser costs are accounted for in ADAM, as are savings for N and P. However, given crop requirements for N and P (see Table 2), and given that like slurry or manure, nutrients in digestate cannot be separated out, either N or P may become a binding constraint. As such, some purchased fertilisers will perhaps be required to ensure the balancing of the nutrient economy.

Table 2: *Assumptions regarding NPK crop requirements*

Crop requirements	N	P	K
Grain maize	120	40	60
Grass mainly silaged (low intensity)	160	50	135
Grass mainly silaged (medium intensity)	235	65	220
Grass mainly silaged (high intensity)	310	80	275
Permanent pasture (Medium term grass leys and medium intensity)	225	30	25
Silage & grazed (dairy)	169	40	100

Source: ABC (2009)

In examining the nutrient economy of farming systems, ADAM processes number of factors including the types of substrates, the degree of concentration during the AD process, the area of land available for spreading digestate, any NVZ restrictions that might be applicable and the types of crops grown. Furthermore, the AD process concentrates N and P over and above that which would be available from slurries, energy crops, and other substrates fed into a digester. For example, Pereira (2009) argues that experiments on batches of digestate quality for the co-digestion of maize silage and manure shows increases of 20 to 26% for solubilised NH_4 and 0 to 36% for solubilised PO_4 after two months digestion. To reflect this in ADAM, models a modest 15% increase in nitrogen availability, while for no increase in phosphorus is assumed.

2.4 Establishing the capital cost of AD

Establishing the capital cost of biogas plants is not a straightforward task since many projects have unique circumstances reflecting the processing of particular types of substrates, the sophistication

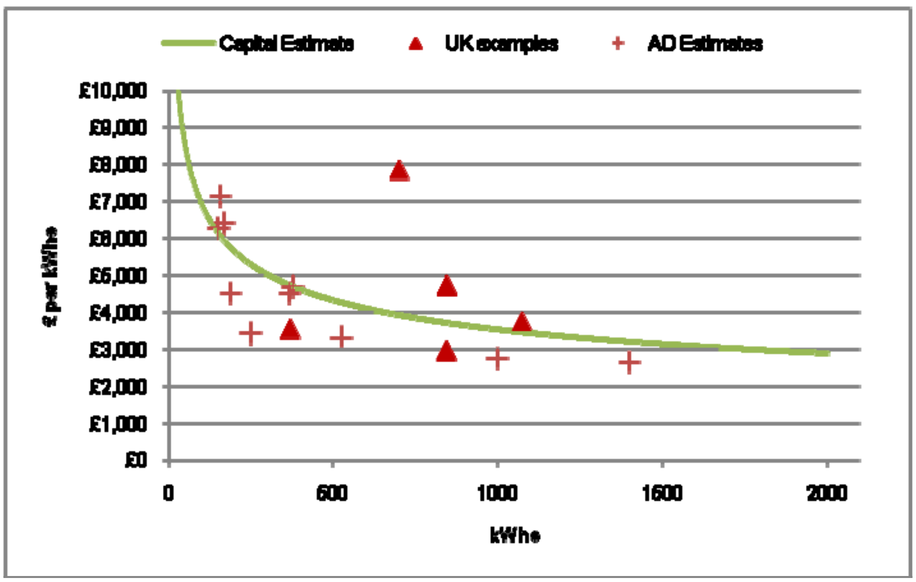
[7] The difference between ADAM's estimates and the manufacturer's estimate only marginally differ by an average of -0.1%.

of technology employed, existing infrastructure on farms, location of plant, and access to grid connections. Andersons (2010) calculated that the capital set-up cost for a biogas plant ranged between £2,500 and £6,000 for every KWh of electricity (kWh_e) generating capacity. To estimate the capital cost of an AD plant, ADAM uses two sources of data: (i) specially commissioned manufacturers' data, and (ii) data from recent (since 2006) planning applications. Figure 2 illustrates the shape of the cost curve that reflects the economies of scale achieved by installing greater capacity. As Andersons (2008) note:

> "*A small plant requires the same facilities as a large one albeit a different scale. Larger plants can benefit from greater economies of scale making the likely return on capital more positive*."

While this is certainly true at one level in terms of basic technologies, the choice of substrates may determine the types of technology that is require. Furthermore, a critical mass of particular substrates may be necessary for greater economies of scale to occur. As such, economies of scale are likely to occur in biogas technology and not necessarily in whole plants.

Figure 2: *Establishing the capital costs of anaerobic digestion plants in the UK*



2.5 Cost benefit analysis

Appraising the economic cost and benefits of AD scenarios on dairy farms illustrates whether projects represent an efficient shift in resources (Hanley and Splash 1994). Therefore, using a Net Present Value (NPV) test enquires whether the discounted benefits outweigh the discounted costs, as expressed by:

$$NPV = \sum B_t(1+r)^{-t} - \sum C_t(1+r)^{-t} \qquad (1)$$

Where B are the expected benefits of a project, C are the expected costs, r is the discount rate and t is the lifetime of the project from the first year of the project (t = 0) and the last year of the project (t = T), which is assumed to be 20 years.[8] The discount rate is set at 3.5% in accordance with the UK Treasury's Green Book value for the appraisal and evaluation of projects, which in this research are the different types and scales of AD plants (HM Treasury undated). Therefore, a Net Present Value (NPV) test, appraises dairy AD plants in terms of (i) economic viability, and (ii) GHGs emissions, as part of the ADAM framework, to assess whether the benefits of an on-farm AD development outweigh its costs.

The costs of AD plants vary considerably reflecting the type of substrates in particular but also different construction costs. The EU-AGRO-BIOGAS project (2008)[9] benchmarking study reported that a number of costs including capital, substrate production and other running cost (e.g. insurance, labour, maintenance and repairs) per kWh_e. By performing a similar exercise,[10] it is clear that the cost of capital is an important factor in the overall costs regardless of plant size. In small-scale AD developments, this can account for up to 50% over a twenty-year period. Also related to the size of an AD plant are the costs of labour and maintenance. Data on labour use at on-farm AD plants was collated from a survey of planning applications and this suggested that for basic on-farm AD plants 0.7 FTEs were required per 1000 kWh_e installed. Finally, the basis of maintenance costs is twofold: (i) on-going maintenance based on manufacturers' recommendations of £0.02 kW_e^{-1} and (ii) the replacement of the CHP every 8 years.

In turning to benefits, ADAM uses the Feed in Tariffs (FITs) system for electrical generation that was applicable from April 2010 (DECC 2010). For larger installations over 500 $kWh_{e,}$ the lower rate of FITs (9p/kWh) is applicable whereas below this size, a marginally higher rate of FIT at 11.5p/kWh occurs. All scenarios are eligible for the export tariff at 3p/kWh. As FITs are linked to inflation, this has been assumed at a rate of 2% per annum. However, as the discount rate is set at 3.5%, over the 20-year period of the AD scenarios, income from FITs marginal decrease. Other income includes the savings from fertiliser displacement in the dairy farm AD scenarios at £0.015 per kWh_e.

2.6 Accounting for carbon

The main CO_2 equivalent (CO_{2e}) emissions created and saved by on-farm AD plants in the generation of electricity include those in the construction process; the production and use of fertiliser; GHG emissions from livestock slurry systems and land spreading of manures; the production of farm-based substrates; and transport emissions from moving substrates from field to the AD plant. In many cases, the use of IPCC guidelines on GHG emissions to calculate carbon equivalent emissions (IPCC 2006) and develop marginal carbon cost curves for AD scenarios.

Embodied carbon in the construction materials of AD plants are estimated using OECD data for emissions from concrete and steel production in developed countries. According to the OECD data, the production of one tonne of steel emits approximately 1.8 tonnes of CO_{2e} while the production of one tonne of concrete emits 0.86 tonnes of CO_{2e}. To estimate the quantity of steel used in the construction of a CHP unit, collated manufacturers' data regarding the weight of units gave an

[8] Also assumes a 20% investment by the developer (dairy farmer).

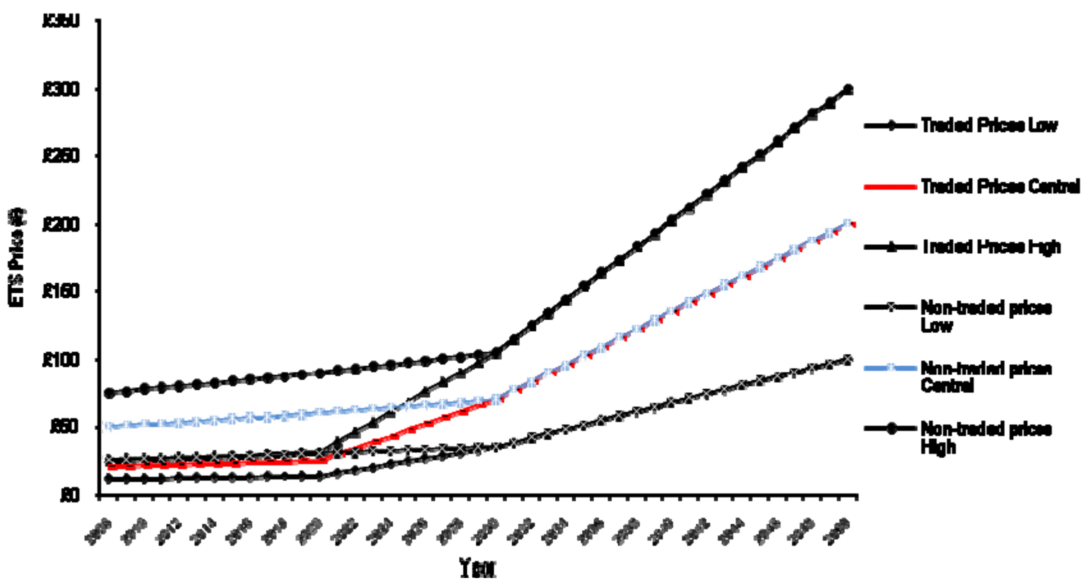
[9] The EU-AGRO-BIOGAS project was a European Biogas Initiative to improve the yield of agricultural biogas plants.

[10] This differs to the EU-AGRO-BIOGAS project in that the benchmarking exercise looked at annual cost rather than total costs over the course of a development.

estimate of tonnes of steel. In considering CO_{2e} from fertiliser, OECD data suggest that on average 2.5 tonnes of CO_{2e} is emitted for every ton of NH_4 fertilizer produced. In terms of fertilizer use, the IPCC guidelines on GHG emissions are used to calculate carbon equivalent emissions (IPCC 2006). To account for the substitution of electricity (and heat) generated by fossil fuel production, Defra/DECC's average for 2007 of 0.507 CO_2 per kWh is used (Defra/DECC 2009).

Turning to the cost of carbon, government recommendations are followed using the shadow price of carbon (SPC) (DECC 2009). The SPC is based upon two sets of carbon price estimates (see Figure 3) which are expected to merge in 2030 when it is assumed that a global carbon market will exist. Therefore, using both sets of figures, one for emissions covered by the EU Emissions Trading Scheme (ETS) (i.e. for steel, concrete and fertiliser production) and the other for emissions not covered by the EU ETS, including agriculture, an assessment of the carbon costs for the AD plant scenarios is made over their expected lifetime (between 2010 and 2030). When examining the shadow price of carbon over this period, a discounting rate of 3.5% is used (see Defra 2007a, Treasury Green Book).

Figure 3: *Shadow price of carbon based on the EU ETS between 2008 and 2050*



3. Results

3.1 AD and the representative dairy farms in the UK

On the representative dairy farms,[11] it is apparent from the farm business survey data (with the possible exception of Northern Ireland) that dairy farms have the potential to grow at least some energy crops as substrates for the AD installation as each produces some arable crops which are sold rather than used as feed. Part of the rationale for adding energy crop substrates to dairy slurry

[11] In the UK according to data from the respective farm business and farm account surveys, the average herd size was largest in Wales with 146 dairy cows and smallest in Northern Ireland with 105 dairy cows (see Table 3). In terms of farm size, the Scottish dairy farm was the largest at 121 hectares while in Northern Ireland it was the smallest at 79 hectares. To model a dairy farm for the UK as a whole, a weighted average was calculated to reflect dominant characteristics from each country.

reflects the low value in terms of energy content that is present in dairy slurry once it has been ruminated by livestock. Table 3 illustrates AD on representative dairy farms in the UK. It is not surprising that the production of biogas and its conversion into electricity is not a viable venture. However, it is noticeable that English and Welsh dairy farms benefit from both additional slurry and small quantities of energy crops that once digested produce a higher biogas yield, as compared to the typical Scottish and Northern Irish dairy farms. In terms of opportunity cost, introducing biogas production as compared to the continuation of farming without AD, suggests that at this scale the continuation of farming without AD is preferable. Finally, Table 3 illustrates the nutrient balance for N and P. On all farms, both N and P in digestate do not compromise crop requirements.

3.2 Scale, profitability and on-farm AD

To examine the profitability of AD installations on dairy farms it is necessary that income from electricity sales is sufficient to repay any capital borrowings. To achieve this, each representative farm was scaled-up to enable annual profit from biogas production to break-even using the following scaling factors: England dairy (3.97); Scotland dairy (3.64); Wales dairy (3.67); Northern Ireland dairy (4.29) and UK dairy (4.08). By scaling up each representative farm, the same proportions of substrates are used but at greater quantities enabling enough biogas production to break-even. Thus, each scaling factor is associated with the point where the annual costs and benefits of biogas production equate so that profit equals zero (see Table 4).

Assuming a payback period of eight years covers all capital costs before any major overhaul of the technology is required, particularly regarding the CHP unit. Using this assumption, the UK dairy farms would need to provide enough slurry and energy crop substrates to power a 156 kWh_e AD installation. In terms of the nutrient economy, since the representative farms have been scaled-up using the same proportions of substrates there are no changes in the balance of N and P supply with crop requirements.

The scale of dairy farms required and output of electrical energy output varies between different countries of the UK. The Scottish representative dairy farm requires least scaling to break-even. This occurs with an output of 108 kWh_e, 444 dairy cows on a farm of 440 hectares, of which 38.5 hectares is used to grow energy crop substrates. A particular factor affecting scale is the ratio of land allocated for dairy to that allocated for arable production. Farms with more arable production, such as those in England and Wales, are able to produce greater quantities of energy crops as substrates, although this also increases costs. In Scotland and Northern Ireland, the scaling of farms reflects that AD is likely to be more reliant on slurries as substrates. While additional energy crops undoubtedly improve the economics of on-farm AD, other factors have an influence. For instance, the representative Scottish dairy farm is more heavily stocked thus producing more slurry substrate from less land than the scaled English dairy farm. The value of volatile solids (VS) is a further complicating factor. When the DM and oDM contents of dairy slurry are at their minimum and maximum limits, the values for VS are significantly different. It is notable that, while slurries have little energy content compared to energy crops, its DM content impacts upon the amounts of biogas produced. In the case of the scaled representative UK dairy farm, when slurry is at its minimum DM content, assumed to be 6%, only 141 kWh_e may be generated whereas when DM content is 11% this increases to 170 kWh_e. The impact per year on biogas profit for the scaled-up representative dairy farm is approximately £9,808, which is about £2,000 per 1% change in the DM content of dairy slurry. In considering the impact on total profit (farm plus biogas enterprise profit), a 1% change in the DM content is worth £3,127. Therefore, the difference in farm profit on dairy farms when modelling the maximum and minimum values for DM content of dairy slurry is £15,633. The rise in profit results from more substitution of fertiliser for digestate. As the DM content of dairy slurry improves, this leads to augmented levels of N and P in slurry reducing the potential amount spent on fertilisers. For example, with a minimum DM content of slurry at 6% the digestate is likely to produce 36.7% of N and 65.7% of P, or 69 $kgNha^{-1}$ and 26 $kgPha^{-1}$. At 11% DM content, nutrients increase to 92$kgNha^{-1}$ and 34$kgPha^{-1}$, thus increasing the percentage of N and P available in the digestate, although these are still within farm and crop requirement limits.

The reality of dairy farms being similar to the representative farms is limited. Arable land on some dairy farms may be more than adequate to increase the scale of grass and maize silage for profitable biogas production. For other dairy farms, it may feasible to use additional energy (food and non-food) crops. For example, incorporating residual food from a nearby food processing facility as an additional substrate can increase the scale of production in terms of biogas and profit. However, the introduction of food wastes has implications for both the technology installed and the operation of the AD plant (Andersons 2008). For example, the pre-processing of certain food residuals may require hygienisation, which increases the cost of biogas plants as well as increasing labour time required to prepare substrates. However, these may be off-set by the possibility of additional revenue from gate fees and provides additional nutrients in digestate. Using the example of the scaled representative UK dairy farm, with an additional input of 10,000 tonnes of food residue,[12] the on-farm AD installation could generate 484 kWh_e, and realise a profit of nearly £1m over a twenty year period. However, over 1200 ha of additional land would be required to dispose of the digestate.

[12] It is assumed that the food residual has a DM content of 23% and a protein content of 17%. Further assumptions include no gate fee is realised, additional capital costs, maintenance and labour costs are incurred to process the food residue.

Table 3: Anaerobic digestion on representative dairy farms in the UK

Country	**Farm**		**Energy production**			**Nutrient economy (digestate)**						**Annual enterprise profits**			
						In digestate		**Requirements**		**Nutrient Balance**					
	Herd size	Area (ha)	Biogas yield m^3	kWh_e	kWh (heat)	N ha^{-1}	P ha^{-1}	N ha^{-1}	P ha^{-1}	(100% = balance)		Farm profit	Biogas profit	Total profit	Opportunity costs
UK dairy	122	109	162,674	38	60	81	30	188	39	42.9%	76.0%	£74,203	-£21,742	£52,461	£54,545
England	121	117	172,856	40	63	76	28	191	39	39.7%	72.4%	£76,829	-£22,772	£54,057	£58,046
Scotland	122	121	126,589	30	52	69	25	195	37	35.2%	67.4%	£57,606	-£17,633	£39,973	£46,406
Wales	149	110	175,348	41	63	95	35	183	40	51.8%	86.2%	£90,261	-£21,502	£68,759	£62,430
Northern Ireland dairy	105	72	57,118	13	35	90	32	172	38	52.4%	84.2%	£57,242	-£11,836	£45,405	£48,167

Table 4: Break-even on scaled versions of the representative farms in the UK (assumes 25% owners capital with borrowed capital repaid in 8 years)

Country	**Farm**		**Energy production**			**Annual enterprise profits**			
	Herd size	Area (ha)	Biogas yield m^3	kWh_e	kWh (heat)	Farm profit	Biogas profit	Total profit	Opportunity costs
UK dairy	499	445	666,608	156	183	£319,556	£0	£319,556	£280,554
England dairy	483	465	687,957	160	189	£325,262	£0	£325,263	£286,688
Scotland dairy	444	440	460,653	108	133	£210,602	£0	£210,602	£183,071
Wales dairy	549	404	645,506	151	178	£336,099	£0	£336,099	£293,671
Northern Ireland dairy	450	309	245,531	58	81	£277,610	£0	£277,610	£260,093

Table 5: *Sensitivity analysis of dairy slurry substrates on the farm and nutrient economies*

Country	**Energy production**			**Nutrient economy (digestate)**						**Enterprise profits**		
				In digestate		**Requirements**		**Nutrient Balance**				
	Biogas yield m^3	kWh_e	kWh (heat)	N ha^{-1}	P ha^{-1}	N ha^{-1}	P ha^{-1}			Farm profit	Biogas profit	Total profit
UK Dairy (average DM @ 8.5)%	666,608	156	183	81	30	188	39	42.9%	76.0%	£319,556	£0	£319,556
UK Dairy (max DM @ 11%)	727,576	170	198	92	34	188	39	49.2%	86.3%	£325,380	£9,808	£335,189
UK Dairy (min DM @ 6%)	605,641	141	168	69	26	188	39	36.7%	65.7%	£312,738	-£9,038	£303,700

3.3 Carbon costs and benefits of AD plants in the UK

In terms of maximum benefits, on a representative UK dairy farm, an AD plant is likely to produce £0.25 million of CO_{2e} savings (7,000 tonnes over the 20 years) for only a modest cost (£0.02 million). However, larger AD plants with sizeable output can potentially make the greatest carbon savings. While Table 6 gives absolute costs and benefits regarding the SPC for AD plants, Table 7 give the marginal cost for each kWh installed. The benefits associated with the average dairy farm is related to GHG savings associated with a reduction in CH_4 and N_20 emissions from slurry stores and manure spreading operations. Using more energy crops as substrates increases kWh but reduces the relativeness of these emissions.

Table 6: *Discounting the shadow price of carbon (SPC) for AD plant scenarios*

AD plant scenario	SPC NPV (£m)	SPC Benefits (£m)	SPC Costs (£m)
Dairy farm (representative)	£0.23	£0.25	£0.02
Dairy farm (scaled)	£1.08	£1.16	£0.08

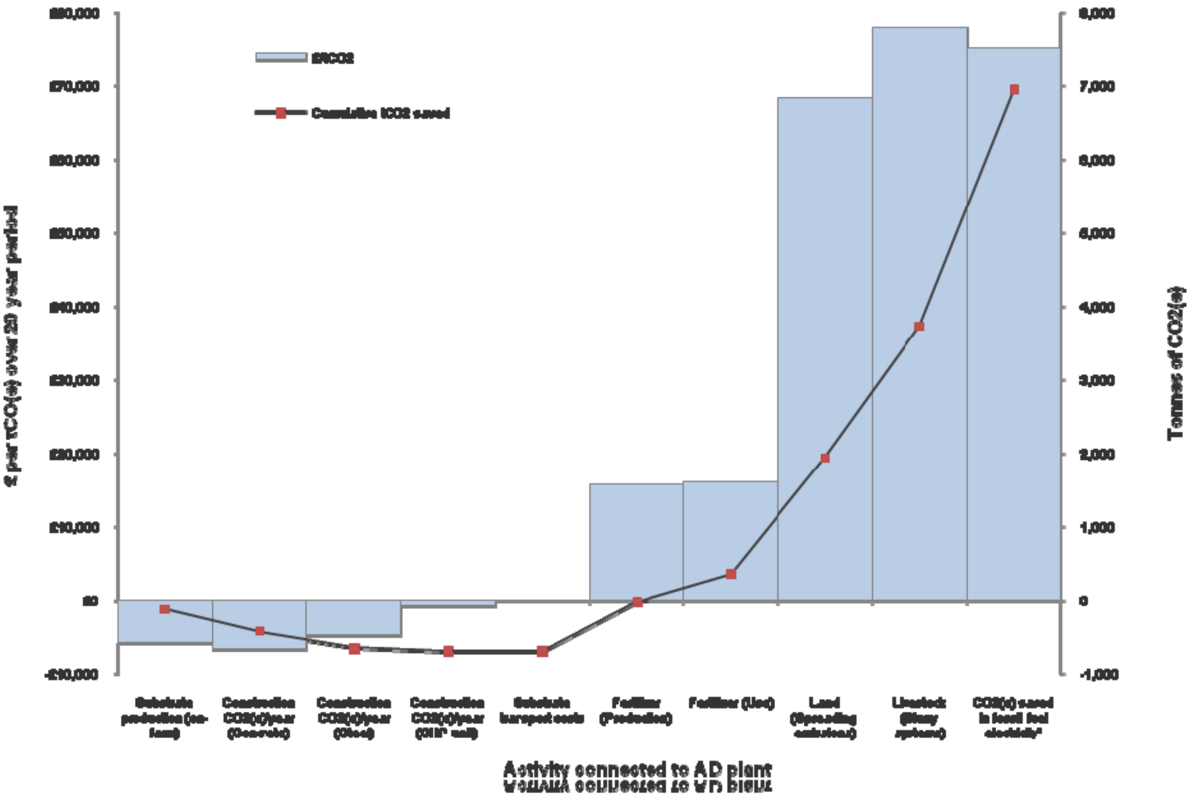
Table 7: *Shadow price of carbon (SPC) per kWh installed for AD plant scenarios*

AD plant scenario	SPC NPV per kWh installed	SPC Benefits per kWh installed	SPC Costs per kWh installed
Dairy farm (representative)	£6,189	£6,665	£476
Dairy farm (scaled	£3,205	£3,455	£249

Illustrated in Figures 4 is the marginal carbon cost curve for representative UK dairy farm with an AD installation. While biogas production on this farm is not economically viable due to its small-scale, it is important to identify how carbon savings can occur, which is less obvious in the results for the scaled representative dairy farm model. The first observation is that while there are some carbon costs in the construction of the AD plants and in the supply of substrates, the benefits are much greater with 42.1% of total tonnes of CO_{2e} saved on dairy farms being attributable to producing electricity from renewable sources instead of fossil fuels. The second observation is the reduction in GHG emissions from livestock slurry systems and manure spreading. For example, on the representative UK dairy farm with AD these account for 23.6% and 20.7% respectively in terms of total tonnes of CO_{2e} saved and 30.7% and 27.0% if costed.[13] From Figure 4, it is clear that even if the electricity generated is additional rather than a substitute for energy produced by fossil fuels, the reduction in GHG emissions associated with livestock slurry systems and spreading of manures outweigh the carbon costs associated with the construction, maintenance and supply of substrates for AD plants on the representative dairy farm.

[13] In terms of value, the SPC for non-traded EU ETS is greater until they converge in 2030, and this is reflected in the differences in benefits that arise between the values for CO_{2e} saved by not burning fossil fuels for electricity production and emissions saved from livestock slurry systems.

Figure 4: *Marginal carbon cost curve per kW electric produced on a representative dairy farm*



Conclusions

ADAM, developed for Defra project AC0406, provides a useful means of analysing the sensitivities of developing AD on dairy farms in the UK and the impact that this would have on their nutrient economies and carbon emissions. In many respects, it is not surprising that the analysis using ADAM concurs with previous research regarding the unprofitability of biogas installations on representative or typical dairy farms found in the UK. For instance, as AEA Technology in 2005 suggest, the economic viability of smaller scale on-farm AD plants are characterised by negative financial returns or at best break-even (AEAT 2005). In addition, a report commissioned by Cornwall Agricultural Council on the feasibility of rural AD installations, including those on dairy farms, came to a similar conclusion (IBBK 2008). One of the key issues drawn out in this research is the role of scale. While the representative dairy may be typical of agricultural scale in the UK, they are not of sufficient size to produce profitable biogas. Indeed, farm scale as represented by FBS/FAS data used in ADAM would have to be at least three to four times larger for a biogas enterprise to break-even.

Developments of AD on dairy farms may occur more frequently in the future as farm and herd size increase. However, this growth is likely to be slow with presently only 3.8% of dairy farms in the UK running herds of 300 cows or more (DairyCo Datum 2010). The advantage of larger farms is the greater ability to resource AD projects in terms of finance but also in commanding enough land to supply the necessary substrates and to optimise the use of the enhanced nutrients in the digestate. If the dairy farm has sufficient arable land, growing more maize and grass energy crops may boost biogas production. Other possibilities may exist for neighbouring farmers to co-operate or form partnerships to manage a biogas installation that processes manures and energy crops to increase the scale of operation. For example, one neighbouring farm might specialise by supplying slurry, while the other may supply energy crops. Alternatively, a farm may choose to import either energy crops or food residues from processing facilities on to a farm, as long as it ensures that any additional substrates do not compromise the nutrient economy of the farm or it can develop sufficient outlets or markets for any excess digestate.

While the economics of AD on representative sized dairy farms is not promising, on-farm AD plants can potentially provide a win-win situation in terms of carbon abatement. They undoubtedly reduce the CO_{2e} emissions that a dairy farm produces as well as the potential for wider CO_{2e} emissions if excess energy exported from a farm displaces fossil fuel produced electricity. A second win are reduced farm costs in terms of energy use and fertiliser costs. Despite these wins, it likely that only larger dairy farms in the UK will realise these benefits since these have the capacity and access to resources to establish economically viable on-farm AD plants.

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