
Calculating the Economic Cost of Mitigating GHG Emissions from UK Dairy Farms by Anaerobic Digestion of Slurry

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Abstract
This study analyses anaerobic digestion (AD) as a renewable energy technology by quantifying the emissions avoided and the cost incurred in the process. The quantitative model developed and demonstrated uses basic farm information to evaluate dairy farms from an environmental and economic perspective. Based on the cost of installing and operating an anaerobic digester and the emissions avoided using this technology, the marginal carbon abatement cost (MAC) is calculated. The MAC thus obtained is used to analyse current policy incentives thereby bridging the gap between the environmental impacts, the economic (dis)incentives and sustainable farming practices.

Keywords
Anaerobic Digestion; Dairy farming; Emissions; Economics; Policy

INTRODUCTION

A change in farming practice in the UK could have a positive impact on reducing the country's greenhouse gas (GHG) emissions, both directly and also indirectly by offsetting fossil fuel usage. Directly, farms contribute 36% of the UK's methane (CH_4) emissions from livestock and livestock manures and 67% of nitrous oxide (N_2O) emissions from the use of either livestock manures or artificial fertilisers (DEFRA, 2009a). The UK's Low Carbon Transition Plan 2009 (HM Government, 2009) aims to cut by 2020 the GHG emissions from waste and farming by 6% based on 2008 levels. Indirectly, farming could also offset fossil fuel usage by both being a net producer of renewable energy and by reducing its dependence on inorganic fertilisers which have a high energy demand in their production. The Renewable Energy Directive (Directive 2009/29/EC) ('RED') will require the UK to source 15% of its energy needs from renewable sources by 2020 which will require a major step change to bring this about from the 2.2% production reported for generation from renewable and waste sources (DECC, 2009a).

On-farm anaerobic digestion (AD), in conjunction with good farming practices and support from the government, can make a contribution to meeting both of these targets. Another benefit is the role that AD can play in development of the rural economy by providing additional revenue to the farmers through the sale of energy, usually in the form of heat and electricity.

Following a major shift in carbon valuation policy, DECC (2009b) has moved away from the social cost and shadow price of carbon based on the Stern review, to the cost of mitigating emissions. For evaluating policies related to emissions not covered by EU Emissions Trading Scheme (the 'non-traded sector'), a short term non-traded price of carbon has been set at €72 tonne^{-1} CO_2 eq until 2020 with a range of +/- 50%, based on the marginal abatement cost (MAC) required to meet a specific emissions reduction target (DECC, 2009b). Policy that delivers mitigation cheaper than the non-traded price of carbon is considered to be cost effective.

This paper reports a method to calculate a MAC for AD by quantifying GHG emissions abated through the introduction of AD to a dairy farm and the change in revenue expected by doing so. This approach allows benchmarking policy that incentivises carbon emission reduction by rewarding mitigation and penalising emission. This paper is based on the analysis of four farming scenarios that could be employed in farming, using a modelling tool to estimate GHG emissions and an economic model for the farm and necessary investments for each scenario.

METHODS

Scenarios

The four scenarios used were based on a farm of 84.2 ha with 91 dairy cows and 101 followers (Jackson *et al.*, 2008).

Case 1: represents a partially grazed conventional dairy farm, most common practice in the UK. Dairy cows are housed for 60% of the year and grazed during the rest on permanent pasture. Winter wheat (9.6 ha) and grass silage (28 ha) are grown on farm to be used to feed the dairy cows. Followers are housed for 30% of the year and grazed during the rest.

Case 2: Farming system and land use distribution is the same as case 1 with the introduction of an anaerobic digester fed with slurry from the dairy cows and the followers. Electricity and heat produced is used in the dairy and surplus is exported to the grid. Digestate produced is used as an organic fertiliser applied using a trail hose spreader.

Case 3: Dairy cows are housed all year. Winter wheat (9.6 ha) used to feed the cows. Followers are grazed on a permanent pasture (28 ha) for 70% of the year. Rest of the land is cultivated for grass silage for the housed dairy cows and followers.

Case 4: Farming system and land use distribution is the same as case 3 with the introduction of an anaerobic digester fed with slurry from the dairy cows and followers. Biogas and digestate are handled in the same way as case 2.

Emissions Model

An emissions model was built to take into account the sources of GHG emissions identified on a dairy farm.

Enteric Emissions. It is assumed that CH_4 produced in the rumen of cattle as a by-product of fermentation is proportional to feed consumed and is all expelled enterically (IPCC, 2006). The enteric emissions were calculated based on the feed intake assuming the weight of a dairy cow is 650 kg (DEFRA, 2010), milk production 6,389 litres year^{-1} (Jackson *et al.*, 2008), fat content of milk 3.5% (Nix, 2007), digestibility of grass 70% (IPCC, 2006) and 6.5% of gross energy in feed converted to methane (IPCC, 2006).

CH_4 emissions from manure management. It is assumed that each cow produces 1.7 tonne head^{-1} year^{-1} of excreta as volatile solids (DEFRA, 2010). When grazed this is distributed evenly on the pasture and when housed it is collected as a liquid slurry. The ultimate CH_4 yield is of excreta was

taken as 0.24 m^3 CH_4 kg^{-1} volatile solids (IPCC, 2006). The average air temperature for the UK is 10°C (The Met Office, 2011). When slurry is used in association with AD on the farm it is fed directly to the digester from a sealed reception tank and the emissions are restricted to fugitive emissions from the digester itself. These will depend on the digester design, construction and management but were taken to be 3.5% of the gross methane production (Silsoe Research Institute, 2000).

There is limited quantitative data available in the literature on the emissions from field application of digestate and IPCC (2006) does not specify any emission factors, so the factors recommended for slurry have been used which may lead to some variability in results. The emission factor (EF) depends on soil moisture content, method of application of digestate, nitrogen application rate, soil type and type of vegetation (Sanger *et al.*, 2010; Senbayram *et al.*, 2009; Moller *et al.*, 2009; Wulf *et al.*, 2002; Amon *et al.*, 2006).

N_2O emissions from manure management. Liquid manure has a low redox potential and hence N_2O is not formed or released when in this state (Rodhe *et al.* 2009). There may, however, be N_2O emission when a dry crust forms on the surface. To account for this an EF for storage tanks with a natural crust cover was taken as 0.005 kg N_2O-N kg^{-1} N added (IPCC, 2006) and the rate of excretion of N by dairy cows as 0.27 kg N $head^{-1}$ day^{-1} (DEFRA, 2010). It is assumed that there are no nitrogen losses from leaching while the manure or digestate is in a storage tank. Emissions originating from volatilisation of N from stored manure as ammonia or oxides of nitrogen have been calculated as per IPCC (2006).

N_2O emissions from managed soils. IPCC (2006) emissions factors were used taking into account the N additions to the soil. Manure to soils was estimated based on amount of manure excreted and its nitrogen content. Emissions from mineral fertiliser were based on N application rates either to meet the requirements of crops (DEFRA, 2010) or using guidelines set for Nitrogen Vulnerable Zones in the UK (DEFRA, 2009b). Indirect emissions from volatilisation/atmospheric deposition and leaching/runoff were estimated based on IPCC (2006). No change in land use has been assumed.

GHG emissions from farm activities. All farm machinery is assumed to use diesel fuel and the energy required for the farming operations was calculated using the method and data in Salter and Banks (2009). A UK-specific emissions factor (EF) of 0.27 kg CO_2 eq kWh^{-1} was used to determine GHG emissions from the diesel consumed (DECC, 2009a). The GHG emissions from the production of mineral fertilisers were based on EF of 7.11 kg CO_2 eq kg^{-1} N, 1.85 kg CO_2 eq kg^{-1} P_2O_5 and 1.76 kg CO_2 eq kg^{-1} K_2O (DEFRA, 2009c).

GHG emissions from dairy energy import/export. The annual electricity consumption on a dairy farm was estimated as 306 kWh cow^{-1} (DLTech Inc, 2006). The GHG EF used for electricity consumption was 0.54284 kg CO_2 eq kWh^{-1} (DECC, 2009a).

Embodied carbon in AD. The size of the digesters, 95m^3 and 143m^3, was calculated using a slurry loading rate of 3 kg VS m^{-3} day^{-1}. Based on this size the embodied carbon in the digester was calculated as per Hammond and Jones (2008). In doing this it is assumed that the digester has a life of 20 years. The gas collected both from the digester and from the gas-tight digestate storage tank was used to produce electricity via a combined heat and power (CHP) unit.

Economic Model

The model assumes that livestock, land and all the dairy buildings and equipment are owned by the farmer. Annual costs for crop and milk production were calculated from Nix (2007). The current price of electricity bought is taken as 11.8 c kWh^{-1} and of gas as 3.5 c kWh^{-1} (DECC, 2009a). In order to account for the recent fluctuations in market price of wheat, a 5-year average (August 2005 - 2010) of €135.6 $tonne^{-1}$ was taken. Similarly a 5-year average of 26.5 c $litre^{-1}$ (August 2005 - 2010) was taken for the farm-gate price paid to the farmer for milk.

A useful rule of thumb for calculating capital cost investment for AD is €3,000 to €7,200 kWe^{-1} generated or €480 to €900 per m^3 of digester capacity (The Anderson Centre, 2010). A high-end value of €900 per m^3 was used as economy of scale is expected to work against the small scale of the farms considered. The lifetime of a CHP unit varies from 8-12 years with a major rebuild after 2-3 years. The total price of the CHP unit, replacement and rebuilds, for a 20-year period is assumed to be €46,800. A mortgage rate on the investment required to set up an AD plant has been assumed at 9% over a period of 20 years (personal communication with banker), higher than the 7% recommended by the IBBK (2008) and the Anderson Centre (2010). Operating costs for the digester including labour, maintenance, repair, and insurance have been estimated at 7% of capital cost (IBBK, 2008; The Anderson Centre, 2010). Net profit is calculated based on enterprise cost, running expenses and value of produce. Current policy incentives like feed in tariffs and the renewable heat incentive have not been built into the model. The effects of these incentives are analysed using the model.

Loss in profit by introduction of AD is calculated by comparing the farms with AD with the corresponding base cases. The loss is then compared to the tonnes of CO_2 equivalent GHG emissions abated by its introduction. Thus a MAC is obtained in £ $tonne^{-1}$ of CO_2 eq abated. Payback period is calculated assuming that a mortgage is not taken and all the upfront investment is made out of pocket. The subsequent additional profit earned by the sale of electricity and heat goes towards recovering that money.

RESULTS AND DISCUSSION

Emissions Model

The emissions for the four cases are presented in Table 1.

Table 1: Results from emissions modelling (kg CO_2 eq ha^{-1} yr^{-1})

		Case 1	Case 2	Case 3	Case 4
		Partial housing	Partial housing plus AD	Full housing	Full housing plus AD
Methane					
Enteric Emission		4,334	4,334	4,246	4,246
	Dairy Cows	*2,903*	*2,903*	*2,815*	*2,815*
	Followers	*1,431*	*1,431*	*1,431*	*1,431*
Manure Management		521	148	745	124
	Grazing	*48*	*48*	*23*	*23*
	Housing	*473*	*100*	*722*	*100*
Fugitive Emissions		0	177	0	264
Nitrous Oxide					
Manure Management		354	0	541	0
	Direct	*197*	*0*	*300*	*0*
	Indirect	*157*	*0*	*240*	*0*

Managed soils		1,958	1,958	1,750	1,750
	Direct	*1,516*	*1,516*	*1,308*	*1,308*
	Indirect	*442*	*442*	*442*	*442*
Carbon dioxide					
Farm activities		634	634	708	708
Electricity and Gas imported		195	-290	195	-541
Embodied carbon in AD		0	17	0	22
Total (kg CO_2 eq ha^{-1} yr^{-1})		**7,997**	**6,988**	**8,184**	**6,574**

Enteric emissions account for nearly 50% of the GHG emissions which in the example used ranged from 2,815 to 2,903 kg CO_2 eq ha^{-1} $year^{-1}$ for different housing conditions and are equivalent to 125 to 128 kg CH_4 cow^{-1} $year^{-1}$. This figure agrees with values reported in the literature which are in the range 96 to 120 kg CH_4 cow^{-1} $year^{-1}$ (Lassey *et al.*, 1997; Bruinenburg *et al.*, 2002; Grainger *et al.*, 2009). More enteric CH_4 $head^{-1}$ $year^{-1}$ is emitted from grazed dairy cows as they are more active and consume more energy than housed cows, although this may be compensated for by selective grazing to increase the digestibility of fresh grass. Enteric emissions from dairy followers, modelled at 68 kg CH_4 $follower^{-1}$ $year^{-1}$, fall within the 48 to 88 kg CH_4 per $follower^{-1}$ $year^{-1}$ range reported in literature (Pinares-Patino *et al.*, 2007). The presence of a digester does not affect the enteric emissions.

Emissions of CH_4 from manure are significantly higher when manure is stored from housed animals. In a grazed system manure excreted in the field is mainly broken down aerobically whereas slurry stored in a lagoon or tank is under predominantly anaerobic conditions which encourage the formation of CH_4. The fraction of methane yield converted for grazing cows reported in the literature ranges from 0.8 to 2.5% which is similar to the IPCC value of 1% (Holter, 1997). The methane conversion factor for a slurry based manure management system reported by Rodhe et al. (2009) is 2.7% which is much lower than the IPCC (2006) value of 10-17%. Hence, there may be an overestimation in the CH_4 emissions from slurry management calculated by the model which is based on IPCC methodology.

GHG emissions associated with storage of slurries are minimised in an AD plant if the feed slurry and the final digestate are held in gas-tight storage tanks connected to the biogas collection system. This is not always the case and if they are not then the overall emissions would be much higher than the estimates given. A poorly run or designed AD plant may also have a high level of fugitive emissions of biogas which, according to the model, would have to increase to 10% to be more damaging than open manure storage tank. It is therefore critical to monitor the performance of the AD plant on a regular basis.

N_2O emissions from manure management are in the order of 5% of the total emissions, but were shown to increase with housing as more slurry is stored in manure storage tanks. The model assumes there are no N_2O emissions from stored digestate.

N_2O emissions from managed soils were higher in cases 1 and 2 where partial grazing took place due to a higher direct loss of N from excreta deposited on the field than from the application of the slurry and digestate. The recommended fertiliser requirement for grazed grass is lower than that for grass silage due to better recirculation of nutrients in grazed grass, thus affecting the amount of fertilisers used and the emissions from their production and application. The emissions from crop production increase with the increase in housing as more grass silage is grown which requires more intervention than a grazed pasture. For the purposes of the model it is assumed that emissions from digestate spread to land were the same as from manure used in the same way.

In cases 2 and 4 the anaerobic digestion plant reduces GHG emissions by 1 and 1.6 tonnes CO_2 eq ha^{-1} $year^{-1}$. AD adds emissions from embodied carbon in the building materials used for its construction. These emissions account for 0.3% of the total emissions per hectare, as compared to other sources of emissions. In order to obtain optimum gas production, a digester requires heat to maintain temperature inside the digester and raise the feedstock to operating temperature and electricity to run the pumps and other equipment. The emissions corresponding to these are offset by the production of heat and electricity by the CHP unit. In case 2, a total of 78,988 kWh of electricity and 84,768 kWh of heat is generated by a 9 kW CHP unit. After accounting for dairy usage, 40,410 kWh of electricity and 16,359 kWh of heat are available for export resulting in an emissions reduction of 485 kg CO_2 eq ha^{-1} $year^{-1}$. Similarly, when the dairy cows are fully housed, a total of 122,262 kWh of electricity and 131,159 kWh of heat is generated by a 14 kW CHP unit. After accounting for dairy usage, 74,533 kWh of electricity and 32,431 kWh of heat are exported resulting in an emissions reduction of 736 kg CO_2 eq ha^{-1} yr^{-1}. Thus the majority of the GHG savings resulting from the introduction of AD come from the energy produced and from avoided manure management emissions. By increasing the housing period of the dairy cows from 60% to 100%, the total GHG savings can be increased by 6%.

Economic Model

Results obtained from the economic model are given in Table 2.

Table 2: Results from economic model (€ ha^{-1} yr^{-1})

	Case 1	Case 2	Case 3	Case 4
	Partial housing	Partial housing plus AD	Full housing	Full housing plus AD
Costs				
(AD) Mortgage	0	173	0	229
Seeds	11	11	13	13
Fertiliser	47	47	54	54
Feed (wheat, grass)	279	279	383	383
Concentrates bought	25	25	25	25
Bedding	23	23	39	39
Vet and medicine	51	51	51	51
Water	36	36	36	36
Electricity	39	0	39	0
Heat	4	0	4	0
Labour				
Crops	140	140	212	212
Dairy	459	459	459	459
AD	0	20	0	31
AD maintenance	0	36	0	53
AD insurance	0	15	0	23
Total	**1116**	**1317**	**1315**	**1608**
Value of Produce				
Electricity	0	57	0	104
Heat	0	7	0	14
Wheat	124	124	124	124
Straw	14	14	14	14

Silage	156	156	259	259
Milk	1831	1831	1831	1831
Total	**2125**	**2188**	**2228**	**2346**
Profit	**1009**	**872**	**913**	**738**

Labour costs account for 50% of the running costs on a dairy farm while the majority of the revenue comes from sale of milk. The feed produced (wheat and grass) is consumed on farm hence there is no profit or loss from its production and consumption. With increased housing, becoming more common as herd sizes and distance to grazing increase, the silage requirement and the farm activities associated with its cultivation increase resulting in a 10% drop in profit. There is an increased energy usage on farm related to maintenance of digester temperature and electrical needs of pumps and other related equipment. Increase in heat and electricity use on the farm is offset by their production for use on farm with the surplus exported. The sale of electricity and heat at 11.8 c kWh^{-1} and 3.5 c kWh^{-1} generates revenues of €107 and €161 ha^{-1} $year^{-1}$ in the two farms, by export of energy and by avoiding its import. The capital cost of AD has been estimated at €85,500 and €128,700 for digester capacities of 95 m^3 and 143 m^3 respectively. The extra revenue from the sale of heat and electricity is negated by mortgage payments of €173 and €229 per ha^{-1} $year^{-1}$ on the capital cost and additional running costs. The digestate is given no financial value as it is not sold off the farm although it has some value as a fertiliser replacement. The net profit after the introduction of AD drops by €137 ha^{-1} $year^{-1}$ in a 60% housed dairy farm while it drops by €175 ha^{-1} $year^{-1}$ in a fully housed farm. AD does not affect the medical, bedding, water requirements, milk yield and the corresponding costs and revenues in a dairy.

Introduction of AD on a typical dairy farm with cows housed for 60% of the year decreases the GHG emitted by 1 tonne ha^{-1} yr^{-1}. Payback period if the capital investment is made out of pocket has been calculated as 29 years. The MAC for GHG is calculated to be €136 $tonne^{-1}$ CO_2 eq abated. Taking the current feed in tariff (FIT) of 13.8 c kWh^{-1} and renewable heat incentive (RHI) of 6.6 c kWh^{-1} into account, the MAC drops to €120 $tonne^{-1}$ CO_2 eq abated and the payback period to 20 years, making only a marginal difference to the farmer. Similarly, introduction of AD on a 100% housed dairy farm decreases the GHG emitted by 1.6 tonne ha^{-1} $year^{-1}$ at a cost of €175 ha^{-1} $year^{-1}$. Payback period has been calculated as 29 years and the MAC for GHG as €109 $tonne^{-1}$ CO_2 eq abated. Taking the current FIT and RHI into account, the MAC drops to €90 $tonne^{-1}$ CO_2 eq abated and the payback period to 18 years, again making only a marginal difference to the farmer. These values are on the higher side of the range of MAC range for other green technologies some of which are already subsidised (McKinsey and Company, 2007) and are also higher than the DECC recommended short term non-traded price of carbon. The profitability of AD is sensitive to the interest rate and in this case, a 7% interest would make the MAC comparable to the short term non-traded price of carbon. Based on the given scenarios, in order to make AD feasible, a FIT payment of 20-25 c kWh^{-1} would need to be introduced. This would reduce the payback period down to 10-15 years which is still quite high. The FIT and RHI may provide some support to the farmers interested in AD but do not go far enough to incentivise its adoption. Current policy structure drives maximum production of electricity rather than the reduction in carbon footprint which is where the real benefit of the technology lies. A restructured policy that rewards abatement and penalizes excess emission based on MAC is required.

CONCLUSIONS

According to the model, operating an on-farm digester reduces the GHG emissions from dairy farming at this scale by 1-1.6 tonne CO_2 eq ha^{-1} $year^{-1}$. MAC using an on-farm AD is €136-175 $tonne^{-1}$ CO_2 eq GHG mitigated. The FIT and RHI may provide some support to the farmers interested in AD but do not go far enough to incentivise its adoption. A green investment bank is being set up by the UK government to provide the extra support needed to green technologies through equity, loans and risk reduction. While these are steps in the right direction, we are a long way from realising the full potential of on-farm AD in the UK.

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