Integrated systems for farm diversification into energy production by anaerobic digestion: implications for rural development, land use & the environment

1 Background

The research examined the potential for more widespread introduction of anaerobic digestion (AD) on UK farms, and the contribution this could make to renewable energy production, rural development and diversification of agricultural practice.

Ongoing reform of the European Union's Common Agricultural Policy (CAP) aimed at decoupling support from production, and the rolling out of a new Rural Development Regulation (1698/2005) for the period 2007-2013, present new challenges for policy-makers and land managers. These major initiatives have set a new European agenda intended both to strengthen the rural economy and to protect the environment. In doing so, they have also promoted other land-use activities including recreation, maintenance of biodiversity and natural habitats, and energy production, with the challenge of harmonising these with food production. Greenhouse gas (GHG) emissions from agriculture are a further issue that society must tackle, and the promotion of sustainable agriculture has been identified by the European Climate Change Programme (ECCP) as a means of reducing these and of enhancing carbon sinks. Farming is also seen as a potential provider of renewable fuels from crop and residual biomass that, together with biomass from managed forests, currently provide 8% of the total EU energy supply and a projected 63% share of the renewable energy market [1].

AD could make a significant contribution to meeting these new targets and challenges for agriculture. In livestock management it may be one of the most cost-effective methods of mitigating GHG emissions from manure. The methane captured from manures together with that generated from other agro-wastes and crop biomass can allow farmers to diversify into renewable energy production. Biogas is already widely used in Europe for the generation of heat and power, and there is strong interest in it as a transport fuel capable of meeting Euro 5 emissions standards. AD can also contribute to better nutrient management and reduce reliance on chemical fertilisers; and by targeting selected agricultural biomass for energy production within crop rotations there is potential to improve the ecosystem services provision of farming.

The changes involved in CAP reform have introduced new financial drivers to farming, however, and diversification through the use of AD must have a sound financial basis. Data from Austria and Germany have shown a conservatively-estimated net profit of £600-700 per hectare on farms producing electricity from methane. This is achieved through a subsidy promoting renewable energy that guarantees prices over a 15-year period. Farmers in these countries have thus been able to obtain capital investment loans to purchase anaerobic digesters. In the UK this has not been possible for small-scale producers, due to the market-based trading system for renewable electricity. The system is based on electricity distributors meeting set quotas by purchasing renewable obligation certificates (ROCs) in auction from renewable energy producers: the value of a ROC can therefore change depending on supply and demand. Although in recent years ROCs have traded at prices offering a good return to renewable energy producers, this is not guaranteed; and the trading scheme thus offered little security on which farmers could base a long-term business plan. Even with 100% first-year

[1] Biomass: Green Energy for Europe (2005), 48 pp, EUR 2135, ISBN 92-894-8466-7.

enhanced capital allowances to encourage investment in AD plants [2] and grant support from European funds made available for on-farm biogas installations [3] as part of axis 3 of the EU Rural Development Regulation, adoption of AD on UK farms has therefore been limited.

While the installation costs of on-farm digesters may be offset by grants and low-interest loans, operating costs must be covered by income generation; and the lack of consistent and transparent means of achieving this is another reason for poor uptake by UK farmers. There has been uncertainty over whether the UK Government would promote AD for production of transport biofuel, combined heat and power, or injection into the gas grid, leading to doubts over which technology to install. It is only within the duration of the RELU project that changes in legislation have opened up these possibilities, and added guaranteed prices by the introduction in 2010 of feed-in tariffs for electricity and for heat in 2011. Incentives for the adoption of AD still lie entirely in the supply of renewable energy, however, with no direct subsidies coupled to environmental improvement through GHG reduction or improved nutrient management. This may influence the type of AD plant built and the biomass used, both of which will impact on land use and rural development.

2 Objectives

The aim of the research was to develop and verify rigorous models for analysis of the commercial viability, energetics, land use and societal implications of diversification into on-farm energy production through anaerobic digestion of energy crops, agricultural residues and wastes.

This aim was to be achieved by interdisciplinary research involving engineers, environmental scientists, biologists and economists working together to produce an integrated analysis. Using this approach the potential benefits and risks to the wider rural community resulting from the uptake of this technology as part of an integrated farming system could be assessed. The tools of the research included: detailed review of the literature to establish the current state of the art and the policy drivers influencing technology development and uptake; use of environmental risk-based analysis methodologies to identify benefits and potential drawbacks regarding environmental protection; energy and carbon balance techniques to examine the sustainability of the approach; use of economic models incorporating land and crop utilisation to determine profitability; questionnaires and focus groups to seek opinion from farmers and the public on farm diversification into renewable energy production using AD.

The specific objectives required to meet the overall aim and the outcomes of pursing these are given below. (These are renumbered from the order in which they appeared in the proposal in order to reflect the integrated approach adopted by the partners working towards the common aim):

1) To review policy and regulatory drivers used across Europe to promote farm-based energy production, and to view these in a UK context for promotion of AD as a contributor to rural

---

[2] DEFRA (2006) The Government's Response to the Biomass Task Force Report. London, DEFRA.

[3] ECCP (2006) ECCP I Review: Agriculture. Contribution of the CAP to climate change mitigation. Presentation by A Moreale to Meeting 1 31 January 2006. European Climate Change Programme. http://circa.europa.eu/Public/irc/env/eccp_2/library?l=/eccp_agriculture/presentations_meeting/31-01-06_finalpdf/_EN_1.0_&a=d. Accessed 1 February 2009.

development making use of the results to inform policy and strategic planning - An initial review of UK Government and EU policy and legislative documents and commentaries was undertaken, a report produced and findings published [4]. Further continuous monitoring and review of policy and regulatory issues took place over the life of the project, and the views formed have contributed to changes in UK policy drivers for AD through presentations and input into working groups.

2) To document the state of the art of AD as applied on farms for the purposes of nutrient management and energy production and to use the results as a baseline for development of farm-based digestion models - A working paper was produced and the results disseminated to multiple end-users offering help and advice in response to direct enquiry. This interaction and the feedback from real-life applications was also fed into model development and enhancement of databases.

3) To construct a technical database of processing and engineering options for farm-based biogas production with information on capital and running costs for different plant layouts - A database was constructed from best available published information and through contact with equipment suppliers. The data were subsequently incorporated into energy and economic models.

4) To analyse technical factors that influence the end use of biogas as a fuel source providing a cost basis for assessing the externalities of on-farm energy production and the economic implications and stability of markets for exporting renewable energy off farm as electricity or transport fuel - Analysis was carried out using the models developed, and applied to real-life cases to advise farmers and agro-industry involved in planning digestion projects.

5) To identify crop species and growth stages suited to AD to establish the potential for crop energy productivity on a UK regional basis - Data were gathered from sources including scientific literature, farm survey data, Government statistics and laboratory studies. The data were used to make net energy predictions from crop-based farm-scale digestion

6) To construct an energy-based analysis model for energy farming within the UK using AD technology that will provide net energy yields per hectare based on a whole systems analytical approach - A spreadsheet-based energy model was constructed and results reported in the scientific literature and in technical reports as well as being used in the above case studies.

7) To estimate, for arable and dairy scenarios, the commercial profitability of AD energy production within the system boundaries of the farm by producing a sophisticated model capable of running land usage scenarios at different scales of operation and to verify this model using a case-study scenario approach involving selected farmers – Addressed by construction of a farm-level linear programming (LP) model for commercial dairy and arable farms with embedded AD component. The model was then run to test the economic viability of farm-based AD under a range of market and policy scenarios.

8) To make an energy and financial cost benefit analysis for co-digestion of slurry, farm-produced crop wastes, and commercial food and/or other organic wastes imported onto

[4] Banks C.J., Swinbank A., Poppy G.M. (2009). Anaerobic digestion and its implications for land use. In: What is Land For? The food, fuel and climate change debate. Eds. M Winter and M Lobley. Earthscan, pp. 101-134.

farms in order to assess the feasibility of on-farm digestion without supplementary land use implications - Addressed by extension of the energy and economic analysis using data collected in earlier objectives, from other research projects and through consultations with farmers and waste managers.

9) To assess whether farm energy self sufficiency is achievable and preferable to export of energy off the farm - Different farm types were analysed using energy and economic models and an assessment of each type made. The output from objectives 6, 7, 8 and 9 was also used to develop the case for support for a Knowledge Transfer Secondment (KTS) to further one of the most promising scenarios; this has now been awarded.

10) To assess the environmental benefits and impacts of nutrient management through fertiliser substitution, providing data that supplement the economic and energy models as well as a knowledge base on which an environmentally sustainable nutrient management strategy can be built for the UK, and:

11) To assess the benefits to environmental protection (including GHG and ammonia emissions) and disease management on farms through the introduction of AD as a diversification activity by developing a cost benefit analysis to provide data for an overall ecological risk assessment (ERA) and data input into the central suite of models - Objectives 10 & 11 were combined and addressed through collection and analysis of data from the scientific and technical literature. Impact of AD on nutrient purchases and nutrient cycling was explored at a range of scales on dairy and arable farm types using the farm-level models.

12) To assess the potential benefits to biodiversity in a wider context by developing an ERA-based approach and conceptual models that can be used to identify the response to a wide range of agricultural changes resulting from diversification of the farming system into energy production through AD - Addressed by review of ecosystem services literature on the environmental impacts of agricultural land use change and farming systems, and development of an ERA framework and a semi-quantitative risk assessment methodology for comparative assessment.

13) To assess social, community and economic benefits to the rural community including the potential for job creation and the development of new skills, and some less tangible community benefits that may be regionally variable - Addressed through analysis of the responses to a postal survey mailed to 2000 farmers, and by farm-level modelling, especially in terms of net margin and farm employment, including the use of contractors.

14) To assess the acceptability of diversification into energy production by AD from a public and farmers perspective and to judge the response to any new pattern of land use - Addressed through a consumer-based survey and a number of focus groups.

15) To provide an overall economic and environmental impact assessment of AD in a UK farming context from which policymakers can make decisions on its role in a rural development strategy, and stakeholders in rural and agricultural communities can evaluate the suitability of the technology to local circumstances - Addressed through collation of outputs from the previous objectives and synthesis of the results in forms that are useful to policymakers and stakeholders. The dissemination of this information is through a Policy and Practice Note, a number of popular press articles in preparation or in press, and input into

Government advisory groups that are currently developing a strategy for enhanced uptake of AD in the UK including on-farm systems.

3 Methods

The methods used were mainly derived from standard techniques applied to new areas. These included: review and assessment of the existing scientific, commercial and legislative literature, in order to develop databases of relevant information. These data were then used in the development of models in order to conduct analyses for various farm types and market and policy scenarios of the commercial viability of AD, its energy balance and GHG emissions. Farm-based financial models used linear programming software (GAMS) to optimise the crops grown on the farm and the scale of the AD plant, whilst the energy model is a spreadsheet-based (Microsoft Excel) modular system in which it is possible to select the crops grown, digester inputs and biogas use and thereby derive an energy balance. As it is constantly changing, the current state of legislation was monitored to keep track of changes particularly relevant to AD, both European and UK-based. Societal aspects of the introduction of AD on farms were addressed using postal surveys and consumer focus groups eliciting both public opinion and farmer perspectives. One survey examined farmer attitudes to, and level of interest in, AD, and perception of the barriers to uptake. A second survey examined the attitudes of the wider public to AD, including views on visual intrusion of AD plant on farms, traffic movements, odours, use of digestate on food crops, and willingness to pay additional tax to fund development and further uptake of this technology on farms.

4 Interdisciplinarity

The project was specifically designed to promote interdisciplinary research through its aim of developing models able to integrate the engineering, environmental and economic factors that influence the decision to adopt AD and the choice of on-farm application. The project was further managed to ensure the necessary interaction between disciplines by having joint sessions to consider the evolving policy context in which AD is set and to discuss this relative to engineering and economic feasibility. These internal group meetings were supplemented by regular meetings with an interdisciplinary steering group with members from academia, industry and Government. The jointly-developed financial viability and energy balance models, undertaken by an agronomist and an economist, were used to develop scenarios that were further evaluated by biologists working on environmental risk assessment and nutrient recycling aspects. Feedback from the whole group was then used to formulate the questions used in the farm survey questionnaires and to develop discussion material for the user forums and workshops. The contribution to interdisciplinary research has been to show how modelling approaches applied in engineering, economics and environmental sciences can be used together to provide a more holistic analysis upon which policy decisions could be based.

5 Results

5.1 Policy

The research has monitored policy developments that have enhanced the financial viability of on-farm AD both in the EU and in the UK. These have taken the UK Government from a position of non-commitment to AD as a renewable energy technology to one of strong advocacy. This, to a great extent, has been brought about by three obligations the UK

Government has resulting from an evolving EU framework [5]. First, the UK's *Climate Change Act* sets a legally binding target of ‘at least’ a 34% reduction in GHG emissions by 2020 [6]: this was set in the context of the EU’s commitment to reduce GHG emissions by 20% by 2020 compared to emissions in 1990. Second, EU Directives to promote energy from renewable sources stipulate that at least 15% of the UK’s gross final energy consumption should be from these sources by 2020. Third, 10% of energy used in transport by 2020 must come from renewables, and in this context biofuels are seen as the most likely source.

Financial incentives for on-farm AD investors in the UK are two-fold: there are investment grants (under the EU-mandated Rural Development programme, for example) and other nationally-funded capital investment incentives. Renewable energy production also receives subsidies through the Renewables Obligation on designated electricity suppliers through trading of ROCs, and the Renewable Transport Fuel Obligation (RTFO). The introduction from April 2009 of a new banding system that raised the number of ROCs for each MWh of renewable electricity generated from AD from one to two has advantaged larger AD operators, who have the resources to carry out the fairly sophisticated transactions involved in ROCs trading. For small-scale renewable energy generation, such as on-farm AD units, the government introduced *feed-in tariffs* (FITs) for new installations from April 2010. A *generation tariff* of £0.09/kWh was determined for larger AD plants (>500 kW), but for smaller ‘farm-scale’ schemes the rate is £0.115/kWh. Across all technologies, the *export tariff* was fixed at £0.03/kWh [7]. In a further policy development, the incoming coalition government announced in its *Spending Review* of October 2010 that ‘FITs will be reviewed in 2012, unless higher than expected deployment requires an early review’, and that it ‘has identified scope to cut FIT costs by 10%, to be achieved as part of its next review’ [8]. The feeling in industry and amongst trade associations, however, is that the FIT is too low. As yet there is no incentive scheme for heat, but a new *Renewable Heat Incentive* is planned from June 2011, which would also apply to biogas injected into the national gas grid [9]. Biogas has not emerged as a significant renewable transport fuel in the UK, unlike other EU Member States such as Sweden. In the second full year of implementation of the RTFO, biogas accounted for a barely measurable proportion of biofuels supplied [10].

The Government’s main focus for AD is the 100 million tonnes of ‘food, farm and other organic waste’ produced each year which, it claims, could ‘generate up to 7% of the renewable energy required in the UK by 2020’ [11]. Our energy and economic modelling indicate that digestion of manures which form the largest proportion of these wastes is unlikely to happen without intervention, and there appear to be no policy drivers in place to stimulate this.

---

[5] Swinbank, A. (2009a) *EU Support for Biofuels and Bioenergy, Environmental Sustainability Criteria, and Trade Policy*. ICTSD Programme on Agricultural Trade and Sustainable Development, Issue Paper No.17 (International Centre for Trade and Sustainable Development, Geneva).

[6] http://www.decc.gov.uk/en/content/cms/legislation/cc_act_08/cc_act_08.aspx, last accessed 8 November 2010.

[7] Department of Energy and Climate Change (2010), *Feed-in Tariffs. Government’s Response to the Summer 2009 Consultation* (DECC: London).

[8] http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/renewable/feedin_tariff/feedin_tariff.aspx, last accessed 8 November 2010.

[9] http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/renewable/policy/renewable_heat/incentive/incentive.aspx, last accessed 8 November 2010.

[10] Renewable Fuels Agency (2010), *RFA Quarterly Report 8: 15 April 2009 - 14 April 2010* (RFA, St. Leonards-on-Sea).

[11] ‘Government invites discussion on the future of energy from waste’, 6 July 2010: http://ww2.defra.gov.uk/news/2010/07/06/anaerobic-digestion/, last accessed 8 November 2010.

5.2 Commercial Profitability of AD

The linear programming models, selecting optimal AD plant size based on choice of feedstocks and appropriate crop rotations, show that AD is commercially viable on typical commercial arable and dairy farms at 2009 prices. A unit generating 500kW of electricity potentially adds £175k/year to the net margin of a 300-hectare arable farm. A unit generating 195 kW could potentially add £37k/year to a 550-head dairy farm. It is difficult to generalise on the financial viability of farm-based AD, however, because of the heterogeneous context in which it operates, e.g. farm size, availability of feedstock, scale of plant, geographic location, grid connection and other factors.

Choice of feedstocks
A large array of agricultural crops, crop residues and wastes can be used as AD feedstocks. Conventional thinking is that manures and slurries are the appropriate feedstock on livestock farms and on arable farms maize is the best feedstock. It is also known that digestion of slurries alone is not a high-profit activity and that higher biogas yields can be obtained through co-digestion with ensiled crops. This thinking is based on empirical data, the tonnage availability of slurries, the large biomass yields obtainable from maize and its widespread use as an AD feedstock in some EU countries. Financial modelling in a UK context confirms the case for using animal slurries, but does not confirm the case for maize in the UK, and better returns are obtainable by digesting whole-crop wheat and sugar beet. To accommodate this, the model makes some changes to cropping patterns to balance the crops required for the AD plant and those for sale off the farm. Specifically, the results show that the wheat area is expanded and beet crops introduced at the expense of both maize and oilseeds. Beets replace oilseeds as a break crop. It is therefore unlikely that 'energy farming' through AD would see an expansion in the area of forage maize, as feared by environmentalists, if the feedstock potential of whole-crop wheat and beet crops is realised. The increase in net margin of a dairy farm as a result of AD is small. It is, however, complementary to and can therefore co-exist with dairying, with cattle numbers unchanged. Using some ensiled cattle feedstock to co-digest with the slurry improves gas yield but reduces the number of cattle that can be supported.

AD and nutrient cycling
Modelling has shown that if all crops grown on the farm are used as AD feedstocks, the recycling of nutrients through digestate usage makes inorganic nutrient purchases unnecessary, resulting in a ~16% increase in the net margin. This is higher than for a dairy farm, where nutrients are already recycled back to land. In the case of co-digestion of slurry with some crops a 24% increase is possible.

AD and farm employment
On an arable farm modelling showed a direct labour requirement for AD of 31 person-days, but with 7 person-days saved elsewhere on the farm due to the replacement of maize with wheat. On the dairy farm, the introduction of AD adds 17 person-days to the farm labour requirement and a further additional 7.4 person-days are required due to the switch from oilseeds to more labour-intensive grass silage.

Viability of AD in a changing policy and market environment
The modelling shows that on an arable farm AD would be viable even if commodity prices rose 75% compared to a 2009 base. Crop feedstock production for AD would stop, however, and the digester would be fed entirely with residues, demonstrating that AD based on

complementary feedstocks is relatively unaffected by commodity prices. On a dairy farm a 50% increase in silage price reduces the size of the AD plant by half and silage ceases to be a feedstock. Further price increases therefore have no effect, i.e. the AD unit is smaller and sustained entirely using slurries. On the arable farm, the AD unit survives a 50% reduction in feed-in tariff, but falls in scale from 495kW to just 85kW. When the feed-in tariff is withdrawn, AD disappears completely. AD would be eliminated from the dairy farm should the feed-in tariff be cut by more than 40%

Importation of feedstocks onto the farm
If additional feedstocks are available the arable farm can import them, leading to an increase in digester size and output. The dairy farm can also import feedstocks (crops in preference to livestock slurries) to increase energy output. Importation ceases when the capacity of the land to accept the digestate is reached. If a nutrient-free feedstock (e.g. glycerol) is imported, the model considers this and further increases digester size and output.

There is much talk in the UK AD sector about the real value in AD operations coming from gate-fee receipts; this modelling exercise shows farm-based AD is viable even without them. The modelling supports anecdotal evidence that the real determinant of the viability of farm-based AD is the cost of borrowing. At interest rates in the range 4-6%, AD is viable, but above this viability becomes questionable. As much as anything else, it is the high rates charged by lenders that have stalled the uptake of this technology in the UK.

5.3 Environmental impacts and benefits

The application to land of digestates from agricultural AD can be environmentally harmful or beneficial. At a local level, the spreading of plant nutrients can substitute for mineral fertilisers and help to maintain soil organic matter. In an intensive livestock farming system handling large amounts of animal wastes, AD can improve the nitrogen availability of fertiliser, making the fertilising effect more predictable. Wise management is required in order to avoid negative effects from gaseous emissions and nutrient leaching, however, as well as from increased field traffic. The implementation of on-farm AD may lead to either a reduction or an increase in total NH_3 and CH_4 emissions, depending on the input materials and the utilisation of the digestates produced. All digestates should be covered during storage in order to reduce emissions. High ammonia losses during the first hours after application must be considered when planning farm operations. Injection technologies can help in reducing emissions on both arable and grassland, while digestate that is surface spread on arable land should be incorporated immediately. Before application of digestates, nutrient compositions and corresponding plant requirements must be carefully matched as differences between the two may result in either over- or under-supply of single nutrients. Under-supply causes a reduction in crop yield, while over-supply may lead to harmful leaching of N and P. The leaching potential from digestates is higher than from undigested slurries if applied in situations when plants cannot take up nutrients (early spring and late autumn); on the other hand, the higher availability of N in digestates reduces the likelihood of leaching when nutrients are applied during the growing season. Liquid-solid separation can make management of the nutrient composition easier. Processing digestates can also help in the development of a marketable product, an option that is likely to be beneficial in avoiding over-supply and minimising required storage space. The implementation of AD on a farm thus has both risks and benefits, but if managed wisely could make a valuable contribution towards improved sustainability in agriculture.

Environmental impact assessment

An ecosystem service approach was used to consider how biodiversity and overall environmental quality were affected by AD. The methodology adopted was that developed by the Millennium Ecosystem Assessment in 2005, and now being used in the UK as a National Ecosystem Assessment tool. This allows all services from ecosystems (supporting, provisioning, regulating and cultural) to be assessed and the outcomes linked into policy and regulation. Biodiversity is not an ecosystem service per se but provides the foundation for many of the services. The initial result of the work was a conceptual framework which could be used to undertake the assessment and to consider any cropping changes driven by adoption of on-farm AD. This was further developed into a management-based ecological risk assessment (ERA) framework capable of assessing the impacts of farm management on functional groups in the agro-ecosystem and used to highlight practices that are most detrimental to ecosystem services provision. The method makes use of a semi-quantitative risk assessment of proxy data for invertebrates and weeds to estimate the effects on three of the ecosystem service groups affected by these functional groups. This approach, however, can only identify trends and overall patterns and does not offer the level of precision that could have been obtained from detailed fieldwork. When considering the changes in cropping patterns resulting from the adoption of AD, this approach identified key risks which were then further analysed using a ‘bow-tie’ risk management approach, pioneered for agriculture by Poppy[12]. Combining risk assessment with risk management in this way has shown how the benefits offered by the technology can be exploited whilst risks are managed, and has provided a further means of integrating the environmental component with economic and energy considerations.

5.4 Energy and emissions

Data obtained through critical review of the literature relating to energy requirements and GHG emissions in farming were used to establish a database of information on production of a range of crops. This information was then used to determine whole-farm energy requirements and GHG emissions, including those of any AD equipment introduced. The results showed that farm energy requirements are strongly linked to fertiliser usage, crop yield and transport distances.

The potential energy output from a farm-based AD unit was derived from the energy value of the biogas produced. This depended on a number of factors including the composition of feedstock materials and the digester design and operation. The research showed that similar amounts of methane, approximately 0.33 m^3 per kg of organic dry matter digested, could be obtained from different plant species harvested in the same way. The largest differences in methane yield from crop materials were the result of harvesting the material at different growth stages: for example straw was shown to produce approximately 50% less methane than whole crop material (harvested when still green and high in moisture content). Crop yield is thus more important than specific methane potential.

Nutrients are required to obtain maximum crop yields but on certain crops, such as wheat, may account for up to 50% of the total energy required for crop production. They can be imported onto the farm as artificial fertilisers; recycled on-farm from crop residues and agro-wastes; or imported to the farm in, for example, the form of food wastes. Where nutrients are

---

[12] Pidgeon, J. D., May, M. J., Perry, J. N. & Poppy, G. M. (2007) Mitigation of the Indirect Environmental Effects of GM Crops. *Proceedings of the Royal Society Biological Sciences,* 274**,** 1475-1479.

bound into organic matter they can be made more plant-available by anaerobic digestion. The results showed that where organic materials with a high nitrogen content, such as food waste, are imported onto the farm, this can reduce or eliminate the requirement for fossil fuel-based fertilisers; but an excess can increase the quantity of nutrient above the capacity of the land to which the digestate is applied.

The farm energy model was used in a number of applications and was shown to be flexible in dealing with quite complex scenarios, due to the modular system adopted using interlinked macro-driven spreadsheets. The model showed that for an average-sized UK dairy farm (108 ha, 122 dairy and 108 other cows) the energy requirement can be calculated at 685GJ including electricity imported for use in the dairy, with a net GHG production of 98 tonnes CO_2 equivalent. The addition of an AD plant digesting slurry from the dairy and housed animals and generating electricity in a combined heat and power (CHP) plant reduces the energy requirement to 481GJ and the net GHG production to 55 tonnes CO_2 equivalent. The energy and GHG savings come from a reduction in the requirement for fossil fuel-based grid electricity. The majority of the rest of the energy and emissions come from the use of fossil fuel-based fertilisers. This requirement can be reduced by importing food waste. The annual import of 680 tonnes of food waste, equivalent to one lorry load of 13 tonnes per week, removes the requirement for imported nitrogen. The food waste also allows the generation of additional electricity which can then be exported to the grid. The result is a net surplus of 453GJ of electricity and a GHG saving of 664 tonnes CO_2 equivalent resulting from the reduced requirement for fertiliser and grid electricity.

5.5 Integration of commercial viability, energy and environmental assessments

The research adopted techniques allowing all of the different drivers and outcomes affecting the process of farm-based AD to be modelled. Outputs were in the form of a number of scenarios that explored different strategies designed to maximise the synergies and overcome the conflicts between the various drivers and outcomes. For example, one scenario used maize as the digester feedstock material because it has high biomass and biogas yields; one of the major disadvantages, however, was the negative consequences from an environmental perspective. It can be hard to reconcile financial and environmental assessments, as the drivers are often in apparent opposition. Thus, when deriving whole-farm implications of the introduction of AD, the modelling process involved combining the three distinct approaches: financial, energy and environmental impact assessment. Integration was achieved through using the outcomes of each approach iteratively to provide input to the others. For example, an initial assessment can be made from an economic perspective, using a range of possible digester sizes and feedstock types to optimise the farm arrangements. These in turn are modelled to determine the energy production and the amount of digestate potentially generated. Similarly, the farm arrangements will determine the storage and application of the digestate and the cropping system to which the ERA is applied. Either the energy balance or the ERA may suggest alternative cropping systems based on improving net energy gains or reducing emissions, and these are fed back into the financial assessment. The results showed there are complexities in the system that make a once-through modelling approach difficult or inappropriate in certain circumstances. For example, the application of fertiliser is governed by climatic, crop and soil considerations and in itself may affect the potential commercial viability of the digester. Restrictions on the application of digestate may result in the requirement for alternative processing options such as drying and wastewater treatment that are not currently included in the models.

The results also showed, however, that if decisions on the type and scale of AD technology required on a farm were made simply on the supply of pre-existing of feedstock then the system would be far from optimal. The modelling approach has shown that in actuality the selection of appropriate AD technology and scale will very much depend on the farming system. By using the three linked assessment methods, it is possible to capture and explore the effects of the often contradictory drivers and the resultant financial, environmental and energy impacts. From this it is possible to develop an overview of the potential effects of the introduction of AD in an integrated farming system, which can be validated against real data.

5.6 Societal implications

Farmer survey

The response rate to the questionnaire sent to 2000 farmers selected from Yell Data was 20.3%, after allowing for responses indicating that the original addressee was a 'non-farmer', had retired, gone away or died. This was regarded as a good response although analysis showed it to be slightly biased towards larger farms and owner-occupiers. 40% of respondents could be described as 'possible adopters' of AD and these showed statistically significant differences from 'likely non-adopters' in that they were from larger farms, were more likely to be owner-occupiers, employed more farm workers, were younger and left full-time education later. In effect, if one regards investing in AD as akin to adopting an agricultural innovation, the survey findings completely support the established view of the profile of an early adopter, as discussed in seminal works on agricultural extension and uptake of innovations by farmers, and borne out by more recent findings on farmer attitudes and decision-making behaviour in relation to setting up new or alternative enterprises. Whilst 'possible adopters' had higher numbers of dairy cattle compared to 'likely non-adopters' of AD, this difference proved not to be statistically significant. This was contrary to the common belief in farming circles that on-farm AD goes hand-in-hand with having a herd of dairy cows, and the consequent problems and/or opportunities associated with the slurry they produce.

The two most important benefits of installing AD were seen by all respondents as 'improving farm profit' and 'reducing pollution/contamination risk'. Significantly more of the 'possible adopters' prioritised the first of these, perhaps indicating that further evidence of the financial potential of AD could result in improved uptake. The most important potential obstacle to the adoption of AD was that 'establishment costs seem too high', closely followed by 'the returns seem too low', although 45% of the respondents thought they could reduce capital costs by doing much of the building works themselves. There was perceived difficulty in obtaining planning permission for the installation of a digester and many of the respondents believed there was insufficient information available on AD.

Respondents identified as 'possible adopters' on average proposed that 21% of their total farmed area could be used for feedstock production, over half of which was growing cereals at the time of survey. By making some assumptions about the crops likely to be grown for AD, and including some of the waste from the 12,000 cattle and 9,000 pigs on these farms, it was calculated that the 'possible adopters' identified in the survey could produce 27.2 Mm^3 of methane per year and generate 95 GWh electricity, assuming a conversion efficiency of 35%.

Consumer survey

The consumer survey gathered views on buying products produced using digestate from AD; attitudes towards Government support for AD; and willingness-to-pay for financial support to farmers to install digesters. A 14.2% response rate was obtained to the four-page questionnaire, covering letter and information pack on AD, which was mailed to 1,500 consumers from Yell Data lists stratified by house value and split 50/50 by urban and rural location. Consumers saw the most important benefit of AD as reducing the need for landfilling of organic wastes. Its role in reducing methane emissions was also seen as important. Most consumers were happy for food and animal feed crops to be used to generate renewable energy through AD; however, manure from farm animals was seen as the most desirable feedstock. As focus groups revealed some perceived problems of AD for consumers, these were examined in the survey: it was found that traffic movements on rural roads and odour were seen as the most likely problems.

Around 70% of respondents indicated that they would be happy to pay higher taxes to provide grants to encourage uptake of AD; 45% said they would be prepared to pay £5 or more per year to do this. The average willingness to pay was £6.53. There were no statistically significant differences between socio-economic groups in this respect.

6 Capacity-Building and Training

Research training has included a RELU ESRC-funded PhD working on the integration of AD in organic farming, and a University of Southampton scholarship-funded PhD developing a model of the economic implications of farm-based GHG emissions. Associated MSc and final-year undergraduate projects have looked at nutrient recycling, energy balance modelling, and hidden flows in agriculture. Members of the research team have presented papers and chaired sessions at national and international conferences, including participation in young researcher forums. The research has allowed two university departments to develop new expertise in assessment of AD projects and has provided continuity for an established group in this field while significantly expanding its areas of interest and knowledge.

7 Outputs and Data

The main data collections relate to the responses from the postal surveys and focus groups, and have been accepted by the UK archive. The energy balance model is available on request and is being successfully used in other research; the economic model and environmental risk assessment frameworks are also available for use and interest has been expressed in further developing the user interface to make them readily transferable. A dissemination event took place at the end of the project and was attended by approximately 40 people from industry, government and non-governmental bodies, academics and farmers. The majority of the outputs will be in the form of peer-reviewed publications and reports. Of particular importance amongst those already published are a book chapter on the relevance of AD in the farming context, and journal articles outlining the policy implications and results of the social surveys. Further publications have already been submitted, with more jointly-authored papers relating to environmental and economic modelling to follow in the coming months.

8 Knowledge Transfer, User Engagement and Impacts

Knowledge derived in the project has principally been transferred through direct contact between researchers and end users or stakeholders, such as those involved in the design and supply of AD plant or farmers who have or are considering setting up an on-farm AD unit. These transfers have involved information flow in both directions, from the project to enable evaluation of the potential of AD in a farming context and into the project in terms of farming-related information (costs, energy usage) used to validate data used in the models. There has been no commercial exploitation of the research to date, although considerable interest has been shown in further development of the farm-level economic optimisation model. A further practical impact has been the provision of advice by members of the research team to Government and related agencies including Defra, DECC, WRAP and the Environment Agency. This has ranged from informal discussions to participation in working groups and peer review of policy documents and research reports.

9 Future Research Priorities

There is considerable scope for extension of the project in terms of application of the various models to actual implementations of farm-based AD, including for validation purposes. These were of limited availability during the life time of the project, as there were very few farm-based digesters within the UK. It would also be valuable to further develop the integration of the financial, energy and environmental models within a ‘real’ farming context. A follow-up survey of farmers who had seriously researched AD as a diversification activity and decided against would be useful in identifying actual barriers to adoption at present.