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

Work Package 7

Modelling the commercial profitability of AD energy production at the farm level within arable and dairy systems

Philip Jones

November 2010

Centre for Agricultural Strategy
School of Agriculture, Policy and Development
University of Reading
Earley Gate
PO Box 237
Reading RG6 6AR
Tel: (0118) 378 8186
Email: p.j.jones@reading.ac.uk

Acknowledgements

This study was funded by a grant from the UK Joint Research Council's Rural Economy and Land Use programme. The author would like to acknowledge and thank a number of colleagues who contributed information to the analysis and commented on drafts of the text. Particular thanks in this regard go to Dr Hannah Jones and Mike Davies of the School of Agriculture, Policy and Development at the University of Reading, Dr Andrew Salter, Department of Civil Engineering at the University of Southampton and an anonymous member of Rural Business Research Consortium, who critically appraised all data and assumptions.

Contents

List of tables

List of figures

Executive summary

Introduction

The work reported here was carried out as part of a three year project, undertaken by the Centre for Agricultural Strategy, University of Reading and the Department of Civil Engineering and the School of Biology, University of Southampton. The project, which was funded by the Joint Research Council's Rural Economy and Land Use Programme, was entitled: 'Integrated systems for farm diversification into energy production by anaerobic digestion: implications for rural development, land use and the environment'. The broad aim of the project was to examine the potential for energy production by anaerobic digestion (AD) on farms, and the contribution this could make to rural development and diversification of agricultural practice. The research reported here deals with the economic viability of farm-based AD in the UK for a range of farm types, exploring such issues as the impact of AD on farm profitability, AD scale, impact on other farming activities, use of different feedstocks, labour requirements, and digestate and nutrient recycling.

Methodology

Economic modelling has been carried out by the development of two representative farm-level models, constructed as Linear Programming (LP) simulation models run on the GAMS modelling platform. Each model represents a single farm representative of their class, i.e. a representative arable farm from the Eastern Counties of England and a large commercial dairy farm from the South of England. The two models project land use and use practice, on the basis of different economic and policy conditions, and the constraints of the available land base. Each farm employs a variety of different agricultural and non-agricultural (i.e. AD) production 'activities' to produce various products, while using a range of different inputs (chemical fertilisers etc.) and resources (labour and different types of land). Within certain constraints, including rotational constraints, land utilisation is varied to maximise the net economic margin of the farm, where this margin is generated from the sale of enterprise outputs, less the cost of the inputs and resources required to produce them. A suite of scenarios were modelled to explore the implication for AD uptake and scale of operation of changes to various states of: the market for electricity; agricultural commodity prices; availability of feedstocks and the energy policy environment.

The economics of AD

In order to demonstrate that AD is economically viable, it is necessary to show that (i) AD can compete economically with alternative uses of crops in order to secure a supply of feedstocks, and (ii) that AD is economically viable at the farm level. Based on 2009 electricity returns and commodity and input process, AD outperforms alternative uses of just four feedstock crops, i.e. fodder beet, wheat, sugar beet and forage maize. For additional crops to be competitive as feedstocks, because methane yield cannot easily be improved, revenues from the use of the methane need to increase, i.e. by means of either higher electricity prices or a higher feed-in tariff. For example, to be competitive as AD feedstocks, minor cereals (e.g. triticale and rye), would require a 3% increase in AD revenues, barley 13% and grass silage 52%. Animal slurries are different, in that their use as a feedstock does not exclude other uses of this same product, for example slurries for nutrient recycling, because AD does not have to compete with other uses for the supply of slurry, i.e. these uses are complementary. Crop residues are also complementary feedstocks. The existence of complementary feedstocks means that AD may be economically viable at the farm level, even when it is not competitive enough to secure the supply of any feedstocks (especially crop feedstocks) that have alternative market-based uses.

However, arable rotations supplying feedstocks for AD cannot use only crops for which AD is the most profitable end use, because a variety of crops are required in rotations to best manage soil nutrients and reduce disease pressure. Broad judgements about the economic viability of AD at the farm level are difficult to make because of the heterogeneous context in which AD operates, e.g. differences in farm size and system, availability of feedstocks, and the scale at which AD is operated. The LP models, which selected an optimal scale of AD operation, together with choice of feedstocks, within a set of crop rotations appropriate for each farm type, show that on typical commercial arable and dairy farms in England, and at 2009 prices, AD is comfortably commercially viable. AD is taken up at a scale of almost one half megawatt, adding £175k to the net margin of a 300 ha arable farm. AD is adopted at 195 kW, adding £37k to the net margin of a 550 head dairy farm. The difference in AD scale between the farms is due to the use of complementary feedstocks, in this case livestock slurry, on the dairy farm, with a lower methane content than crops and digester output is accordingly reduced. In both cases importation of feedstocks onto the farm is not permitted.

The two farm type models demonstrate two different ways in which AD can be operated on farms. In the case of the arable farm AD is a competing enterprise, displacing existing economic activities by appropriating their outputs to serve as inputs to AD. In the dairy case AD is a complementary activity, sitting alongside existing economic activities with minimal displacement (at least, this is the case where digester scale is less than 200 kW). In this case, the model is able to find sufficient feedstocks to operate the AD unit at a profit, without having to reduce the size of the dairy enterprise.

AD and nutrient cycling

Digestate residues are excellent sources of nutrients (mainly N, P, K), with the nutrient profile of the digestate being much the same as the nutrient profile of the feedstock sources. The modelling has shown that if all crops grown on the farm are used as AD feedstocks, then the recycling of these nutrients through the timely application of the digestate to land largely eliminates the need for inorganic nutrient purchases. Under these circumstances only modest nutrient purchases would be required (whether inorganic or otherwise) in order to replace nutrients lost from the soil during the cultivation and growing period, for example through leaching into ground water. Total cost savings on nutrient purchases are far greater for arable farms than for dairy, largely due to the fact that the dairy farm is already recycling AD feedstocks (slurry) back to land. Around 16% of the improvement in farm net margin resulting from adoption of AD on the arable farm is due to savings in the cost of purchased inputs. The purchased nutrient savings on the dairy farm amount to 24% of the net margin increase, because of co-digestion of slurry with some crops.

The choice of AD feedstocks

A large array of agricultural crops, crop residues and organic wastes are potentially available for use as feedstocks in farm-based AD operations in the UK. In terms of choice of feedstocks, conventional thinking is that livestock slurries are the appropriate feedstock on livestock farms, and forage maize on arable farms. The choice of these two is predicated on the availability of slurries, and on the large biomass yields obtainable from maize, together with the relatively common occurrence of this crop in UK agriculture for use as a livestock feed. Forage maize is also widely used as an AD feedstock crop in some EU countries. The analysis presented here confirms the use of animal slurries on livestock farms as an obvious and economically rational choice. However, the endorsement of forage maize as the crop of choice for feedstock is more muted. While maize is one of the three best performing AD feedstocks, in terms of net margin return, it does not provide the largest margin over alternative uses. The modelling exercise shows that wheat and sugar beet are preferable, when harvested whole-crop and ensiled for storage. This finding suggests that the continental model of arable AD, based on maize feedstocks, is not directly transferrable, and that a new UK model needs to be developed, based on the use of ensiled beet and whole-crop wheat as feedstocks.

The impact of AD on cropping pattern and livestock numbers

With the introduction of AD, the arable model does not turn the whole farm over to feedstock production, but some on-farm changes are introduced to allow the supply of feedstocks, specifically that beet crops are introduced and the area of cereals expands, at the expense of both maize and oilseeds. Here beets replace oilseeds as a break crop. Generalising from these results it is apparent that the impact of AD on arable rotations would be fairly minor, i.e. wheat would likely retain its dominant position in rotations, but the role of oilseeds as a break crop may diminish. It is unlikely that there would be an expansion in the area of forage maize once the feedstock potential of whole-crop wheat and beet crops is realised. On the dairy farm, AD is seen to be complementary to dairying and therefore the two co-exist; cattle numbers are therefore maintained. The changes in cropping pattern on the farm are also fairly minor, involving some loss of combinable crops and an increase in grass leys. Grass leys have higher nutrient requirements than most other crops, particularly for P and K, and so an expanded grass area increases the capacity of the farm to absorb digestate.

AD and farm employment

In estimating the consequences for labour use of adoption of AD, account has to be taken of both the labour changes attributable directly to the AD unit, and any other labour changes that might occur as a consequence of adjustments to other farm operations. The direct labour requirement for the AD unit on the arable farm is a little under 31 man days, while the whole-farm labour requirement only increases by 24 man days, i.e. a saving of 7 man days was made elsewhere on the farm, due to the replacement of maize with wheat. Because there are relatively few crops where AD out-competes the alternatives, there will be a tendency on farms taking up large-scale AD units to simplify farm rotations, based around, but not confined to, this limited set of crops. This simplification may result in some labour savings. On the dairy farm, the introduction of AD directly adds 17 man days to the farm labour requirement, but taken over the whole farm labour increases by 24.4 man days, with the additional 7.4 man days due to the switch away from oilseeds to more labour intensive grass silage production.

The viability of AD in a changing policy and market environment

Accepting that AD is economically viable on commercial arable and dairy farms in England and Wales in the current (or rather 2009) market and policy conditions, how robust would the economic model be in the face of changes to this operating environment? This study explored this question by adjusting, in a number of different modelling scenarios, both the policies that support AD on farms and the market prices of agricultural commodities.

At 2009 prices AD out-competes alternative uses in the case of beet crops, wheat and maize. An enterprise net margin analysis suggests that it would be uneconomic to divert any crops to AD uses if commodity prices rose (above 2009 levels) much above 25% (and assuming no corresponding rise in energy prices). However, farm modelling shows that AD is more robust than these calculations suggest. On the arable farm AD is still deployed when commodity price rises reach 75%. In this instance, the production of feedstocks ceases, and the digester is supplied from crop residues, i.e. a complementary feedstock source. This observation demonstrates that AD use of complementary feedstock sources is unaffected by commodity price rises, because there is no alternative market use for these products. This fact bestows a degree of economic resilience on AD, in the face of market price fluctuations, and this is most evident on the dairy farm. The modelling shows that with a 50% increase in commodity prices, the scale of the AD unit operated on the dairy farm falls by half, but that higher rates of price increase have no further deleterious effect on the AD operation, because the AD unit has shrunk to the point that it can be sustained entirely using livestock slurries.

AD is currently supported in the UK by Government renewable energy policy and of most significance in this regard are the feed-in tariffs and the availability guarantees for the export price of electricity. While these policy arrangements are intended to be for the long term, farmers' experience with the changing Common Agricultural Policy has made them wary of assuming continuity of policy, and this an obstacle to adoption. This study sought to explore the impacts of changes to government support for renewable energy generation, primarily through modelling the reduction, or the abolition, of the feed-in tariff. On the arable farm, the AD unit survives a 50% reduction in the value of the feed-in tariff, but the scale of the unit falls sharply from 495 kW to just 85 kW. At this scale the AD unit is supplied only from crop residues. When the feed-in tariff is withdrawn, AD disappears completely. A 50% cut in feed-in tariff would eliminate AD from the dairy farm, but further exploration of this threshold has shown that AD would still be viable with a cut in feed-in tariff of up to 40%.

The importation of feedstocks onto the farm

When imported feedstocks are available, the arable farm increases digester scale by 30%, by importing 4,223t of forage maize (only forage maize was available to import). The dairy farm also imports forage maize (in preference to importation of livestock slurries) to increase AD scale. As with the arable farm, enterprises that outcompete AD (i.e. the dairy herd) are retained and importation ceases when the capacity of the land to absorb the digestate is reached. When a nutrient-free feedstock (glycerol) becomes available, the model imports this and the scale of the digester is increased again. Farms may choose not to turn all of their land over to feedstocks production for a number of reasons, including that alternative uses make a bigger contribution to farm net margin, or because the production of uneconomic feedstock crops is necessary to maintain healthy rotations. In these circumstances farms will turn to feedstock imports where prices are low enough. Ultimately, even with the availability of low nutrient feedstocks, what determines the upper ceiling on AD scale is the availability of land to take the digestate. There is much talk in the UK AD sector about the real value in AD operations coming from gate fee receipts. However, what this modelling exercise has shown is that there is no pressing need for these, or even the importation of feedstocks onto the farm, for AD to be economically viable on commercial dairy and arable farms.

Conclusions

On commercial arable and dairy farms in the UK, AD is economically viable, assuming it is deployed at an appropriate scale and appropriate feedstocks are selected. AD appears to be fairly resilient in the face of higher (than 2009) commodity prices especially when using complementary feedstocks. Lack of availability of gate fees is not a constraint to AD. What does appear to be a constraint however, is the cost of borrowing. AD requires large capital investment, anything from £2-7k per kW, and on most farms this would require significant amounts of borrowing. The cost of servicing this borrowing is critical to the economic viability of AD and anecdotal evidence confirms that high interest rates charged on borrowed capital accounts for the failure of many potential AD projects in the UK.

1. Introduction

1.1 Objectives

The primary objective of this analysis is to test the economic viability of AD in the context of different farm systems in the UK. Within this broad objective a range of subsidiary objectives and research questions have been set and these are outlined below.

1.1.1 Impact on farm profitability

Aside from any constraints that might exist to the uptake of AD in terms of resource availability (these will be addressed below), AD will only be taken up if it makes a positive contribution to the profitability of the farm. This exercise is required to explore the impact of AD on farm profitability, for different farm types and at different scales, taking into account all costs (variable and fixed), including capital costs. This requires an assessment of which activities out-compete AD financially (in terms of profit contribution per hectare), and which are out competed by it?

1.1.2 Farm type

On which farm types is AD best suited? Farms with grazing livestock obviously have a ready supply of feedstock for the digester, in the form of slurry, but crops and their residues generate more methane. Where do the complementarities and conflicts exist, in terms of different farming systems?

1.1.3 AD scale

At what scale can AD be deployed on different farm types and sizes? What are the practical limits to increasing AD size (e.g. disposal of digestate, labour availability, etc.) and what scales are optimal economically?

1.1.4 Impact on other farming activities

What impact does the uptake of an AD activity have on existing enterprises on these different farm types? What activities are complementary to AD, i.e. they either do not compete for farm resources, or supply of feedstocks, or they make use of the digestate, and which activities conflict with AD? How does AD impact cropping pattern and farm rotations?

1.1.5 Use of different feedstocks

A range of different AD feedstocks are available (see Table 5 for a selection of the most commonly used in the UK), including animal slurries, crop residues, a variety of different food crops, animal forages, including grass and ensiled maize, domestic and manufacturing food wastes. Which of these potential feedstocks is preferable in the context of on-farm AD? Is AD viable without the import of feestocks onto the farm? Is AD viable using only livestock slurries?

1.1.6 Labour

What are the labour requirements of AD? Do farms have sufficient labour to operate AD at different scales?

1.1.7 Digestate and nutrient recycling

What financial benefits, in terms of nutrient purchase savings, are possible through uptake of AD and to what extent does the disposal of digestate limit the scale of AD under different farm types?

1.2 Methodology

To achieve these objectives, a work package containing a number of separate sub-components was required. It was recognised at the proposal stage that, at the point of delivery, it may be necessary to vary the detail of the methodology in order to adequately address the research questions and this has proved to be the case. Where such changes have been made, they are explained in the sections below.

1.2.1. Construct a digester cost model

The core of the modelling exercise is the digester cost model. This was developed on a UK basis, taking into account different substrate (feedstock) types and digester configurations identified in work packages 3 and 5. The feedstock database identified all feedstock sources potentially available for use on UK farms, plus the methane outputs of each per kg of fresh material and per kg of dry matter. The economic database for use in the AD cost model included both installation and running costs. Running costs included labour, repairs, insurance, materials, power etc., varied according to substrate type and throughput. Installation costs were accounted as capital costs with a fixed payback period. These operating and capital costs were identified from multiple sources, including work packages 3 and 4, literature review, plus discussions with AD specialists (consultants) existing operators of farm based AD and their plant suppliers and advisers.

1.2.2. Construct farm type models for a number of farm types

No specific approach to the construction of the farm type models was specified at the proposal stage, but two alternative approaches were suggested. First, a spreadsheet-based approach. This would be both simple and transparent and would allow the direct comparison of the economics of AD against a range of agricultural activities. Additionally, in a whole farm context, it would allow an exploration of the impacts on farm net margin of the introduction of AD units at a range of scales. The limitations of this approach are that: (i) decisions on the scale of the AD unit that is introduced have to be taken by the researchers; (ii) the choice of feedstocks also have to be taken by the researchers; and (iii) an infeasibly large number of iterations would be required to identify the 'optimal' AD scale, choice of feedstocks and farm rotation etc. for each farm type.

The second alternative approach was the construction of the farm type models using Linear Programming (LP). LP is an optimisation technique, employing a mathematical algorhythm that identifies the optimum mix of factors (inputs, resources etc.) for the delivery of a particular outcome (in this case maximisation of farm net margin), subject to given constraints (in this case availability of land, labour and capital). The construction and operation of an LP-based model is much more technically challenging than use of spreadsheets, requiring specialist knowledge, and the modelling process is not as transparent. However, the approach does offer considerable advantages over the spreadsheet approach, in that; (i) it removes the requirement for the researcher to specify choice of feedstock, cropping pattern and AD scale (doing this effectively pre-determines the modelling outcomes); (ii) it generates much more realistic outcomes, taking into account, simultaneously, many more of the factors that would determine real-world outcomes, e.g. resource and policy constraints, prices etc; and it generates 'optimal' solutions, having reviewed a multiplicity of choice sets. Because these benefits so heavily outweigh the disadvantages, it was decided to adopt the LP modelling approach.

On this basis, two farm-level models were designed, one livestock based, i.e. dairy and the other, general cropping, to permit the exploration of the use of the widest range of AD feedstocks, i.e. energy crops and agricultural residues and wastes, in a whole-farm context. It was originally proposed that for each farm type, two farm sizes would be modelled, i.e. medium (up to 200 ha) and large (>200 ha), but this approach was dropped, in favour of a single farm size for each farm type, reflecting typical commercial farms of each type. Thus the dairy farm would reflect a typical large-scale housed unit, as would be found in the south of England and the arable farm would reflect what would be typical for this type in the east of England. In part, this reduction in the number of models was an adjustment to allow for the construction of fewer much more sophisticated and robust models within the project resource constraints, but it was also in recognition of the fact that certain of the farm size and AD scale combinations that had originally been proposed were infeasible. In consequence, where it was originally proposed that for each farm type/size combination, large and small digester capacities would be modelled, this notion was also dropped, as the use of the LP approach meant that the model would automatically explore the issue of AD scale and would identify the optimal scale for each farm type, based on the availability of land and different types of feedstock.

It was recognised at the proposal stage that, if the economic modelling of farm-based AD was to be credible and useful to the industry, the profit measure used, both for AD and the farm, had to be some form of net margin, i.e. accounting for fixed costs such as energy, labour (farm and family labour and use of contractors), depreciation and interest charges on borrowed capital. The LP-based farm type models were therefore constructed on this basis.

The structural, technology and economic data on which the farm type models were constructed were derived from multiple sources, including the Defra Farm Business Survey (FBS), published farm management standards, literature review (of AD modelling projects etc.), as well as direct from farm-based operators of AD, their advisers and suppliers. The reason for this diversity of sources was to ground the farm model, and the AD activity contained within it, in reality as far as possible. The general approach employed was to use the FBS and published farm management data in the first instance, but supplement and replace these data where more accurate or up-to-date sources could be identified.

Prior to the construction of the models, discussions took place with a number of farmers who either operated AD units, or who were interested in doing so, and were at an advanced stage of researching the subject. These discussions were useful in identifying technical/agronomic, policy and economic issues that had to be reflected in the modelling. Some of these farmers were able to supply data useful to the modelling and some were recruited to provide feedback on the reasonableness of the models and the modelling outcomes.

1.2.3. Incorporate the AD cost model into the farm type model

Once the farm type models were constructed they were test-run in the absence of the AD activity and the credibility of the outcomes assessed. The digester cost model was then embedded within the farm models, acting as a separate enterprise, but integrated with other farm activities, and so competing for farm resources and subject to farm resource constraints.

1.3 The scenarios

Because it was originally proposed that up to eight farm type models be constructed, it was envisioned that relatively few scenarios would be run. With the reduction of the number of models to two, the number of scenarios that could be run was increased, making it possible to explore a far greater range of policy and market issues. More details on these scenarios are provided in Section 4.

2. THE LP modelling approach

2.1 Overview

The farm models are LP simulation models run on the GAMS[1] modelling platform. These models project land use and use practice, on the basis of economic and policy conditions, and the constraints of the available land base. Each model represents a single farm representative of their class, i.e. a representative arable farm from the Eastern Counties of England and a large commercial dairy farm from the South of England. Each farm employs a variety of different production 'activities' to produce various agricultural products, while using a range of different inputs (chemical fertilisers etc.) and resources (labour and different types of land). In producing these outputs the models use resources (land and labour), which can potentially also be used for non-agricultural rural enterprises, including anaerobic digestion. The farm models are comparative static and based on a single one year business cycle, i.e. they reflect only annual agricultural enterprises, or an annual average of longer-cycle enterprises, such as dairy animals or permanent horticultural crops.

The models allocate different types of land to different activities, subject to specific constraints, some or all of which might be binding under given scenarios:

(i) constraints on the availability of land and labour and the capacity to switch these resources between different uses;
(ii) constraints on the total amount of production by the farm, reflecting the current policy, regulatory, or market limits to supply of products;
(iii) constraints on the use of inputs by the farm business, either due to limited availability, or policy, regulatory, or husbandry limits to their use;
(iv) policy constraints which restrict production activities or land utilisation patterns in certain areas to conform to environmental objectives.

Within these constraints, land utilisation is modelled according to the net economic margins which can be earned by the various activities. These margins are generated from the sale of enterprise outputs, less the cost of the inputs and resources required to produce them. The net margins reflected in the model are thus measures of returns to land, management and capital, with both self-employed and hired labour costs being accounted for in the model estimation.

Each farm activity contributes to the total net margin of the model as a whole. This overall margin is known, in modelling terminology, as the 'Objective Function'. The model is required to maximise this value.

[1] General Algebraic Modeling System (GAMS). GAMS Development Corporation. http://www.gams.de/

2.2 Model structure

The mathematical structure of the farm models are that of an ordinary LP model, that is:

Maximize: $\mathbf{Z} = \mathbf{cx}$

subject to: $\mathbf{Ax} \leq \mathbf{b}$

$\mathbf{x} \geq 0$

where **Z** is the objective function, given as the scalar product of **c** and **x** vectors, **b** is the resource endowment and input availability vector, **c** is the vector whose elements are returns and costs, and **x** is the output vector. **A** is the matrix of input/output coefficients (**aij**) representing the amount of input (**i**) required per unit of output (**j**).

The land surface of the farm is divided into a number of fields, on each of which a variety of production activities are possible, each with an associated requirement for inputs. Table 1 shows the production activities available in the farm models, plus the inputs used to produce them.

Table 1. List of production activities and associated inputs available in each 'farm field'

Enterprises/activities	Inputs
Both models	
Wheat	Labour - regular
Barley	Labour - casual/seasonal
Oats	Contractors
Other cereals	Fertiliser
Peas/beans (for stockfeed)	Crop protection
Sugar beet	Seeds
Potatoes	Other crop costs
Oilseeds	Machinery fuels and oils
Field-scale vegetables	Machinery repairs
Forage maize	Machinery depreciation
Fodder beet	General farming costs
	Land and property costs
	General miscellaneous costs
Dairy model only	
Dairy	Concentrate feeds
Grass silage	Coarse fodder
	Vet and medicine
	Other livestock costs (incl. AI)
	Rearing or purchase of herd replacements

The list of enterprises included in the models have been restricted, by the omission of very many minor enterprises, to prevent them becoming excessively large. This fact, of course, is a limitation, but not a major one, as the models include representatives of all the major classes of enterprise (cereals, oilseeds, break crops, field-scale horticulture and forage crops), and all of the main land using individual enterprises (in area terms) found in England and Wales agriculture. Importantly, there is good representation in the models of the most viable crops that might be used as feedstocks for anaerobic digestion. Other enterprises can be added to the base models as and when particular modelling scenarios require them and in this regard any type of enterprise can be included that draws on farm resources and contributes to the farm net margin, even activities that might not be described as agricultural in nature, such as caravan parks and farm-based recreation and tourism.

The models is not restricted to produce particular volumes of enterprise outputs, i.e. there are no exogenous upper production constraints, as the volumes produced by the individual farms are small enough that it can be assumed that a market will always be available for all commodities produced. Enterprise production volumes are, however, endogenously constrained by rotational requirements and resource availability in the context of competing demands for those resources. The one exception to this rule is milk, production volumes of which are constrained by a policy measure, i.e. milk quotas.

It is up to the model to distribute production of enterprises over the various fields on the farm according to the size of each field and the yields obtainable. Thus, for example, for cereals output, this relationship can be expressed as:

$$\sum_{k=1}^{12} y_{ck} \cdot x_{ck} = C$$

Where: ($\boldsymbol{y_{ck}}$) is the yield of cereals on field k (k=1 to 12), and ($\boldsymbol{x_{ck}}$) is the area of cereals in field K.

Each of these land using activities has associated with it specific requirements for inputs and resources and specific output levels. These are specified in terms of their physical volumes and prices per unit of output or input. Averaged over the farm, yields are representative of yields obtainable on similar farms in the region. However, illustrative yield variation is captured by the different fields on the farm. The division of the farm into a number of separate fields allows for a structured representation of heterogeneity in the yield characteristics of the land base of farms. Agriculture on each farm is carried out at the ‘average’ production intensity observed in practice for commercial farms of each type, where intensity is defined in terms of input use per ha. Stocking rates are set endogenously within certain limits set by cross-compliance conditions. More will be said of this later.

Within the land base of each farm, three major land types are distinguished: arable/ley, permanent pasture and rough grazing. Leys (temporary grass) are sown grasses under 5 years old. While the availability of the different types of land available on each farm is constrained, there is limited capacity to transfer land from one type to another. Because arable land and leys are both considered to be part of the arable rotation, no distinction is drawn between these two types of land in terms of their permitted uses and transfer between the two is not constrained. Transfers are also possible from permanent pasture to leys, but this is constrained to be no more than 10% of the available stock of permanent pasture, reflecting a constraint that only the better quality permanent pasture would be productive enough to warrant arable conversion. Transfers are not possible from arable to permanent pasture and rough grazing land has no alternative uses, reflecting its low fertility and other agronomic problems. Land cannot be transferred from one field on the farm to another.

The models can be operated in either 'policy endogenous' or 'policy exogenous' modes, or both in combination. In the 'policy exogenous' case the effects of alterations in market and policy conditions can be input, in which case the land use and use practice outcomes imply changes in the natural habitat. In the 'policy endogenous' mode of operation, particular characteristics required for the natural environment can be specified as inputs, such a limits to input use, in which case the implications for agricultural and other rural activity returns are determined by the model, which in comparison with the base situation, defines the penalties and incentives necessary to achieve the particular environment specified.

In either mode of operation, or both in combination, the model generates estimates of incomes and returns to resources (land and management) and associated use of labour, which can then be incorporated into farm-level economic and social analysis.

2.3 Enterprise data (input/output coefficients)

The models require data on the output values generated by enterprises in each field of the model farm, i.e. commodity prices multiplied by enterprise yields, and their associated input costs (input volumes * prices) and level of resource use (volume * costs). These 'production relationships' have been derived from the FBS data set and other published farm management sources, and a number of Defra data sources (all sources are referenced).

2.4 Livestock stocking rates

The grazing livestock activities are not constrained, exogenously, to operate at fixed stocking rates; rather, stocking rates are determined endogenously. Each source of livestock feed: grasses of three kinds, fodder crops and purchased feeds, make given metabolizeable energy (ME) contributions to the ME requirements of farm livestock and the model is at liberty to vary the contribution of each of these sources on an enterprise by enterprise basis. Effectively, the greater the contribution of purchased feeds, the higher the stocking rate. Purchased feeds can be in the form of concentrates (which make a relatively high ME contribution) or coarse fodder (which makes a lower ME contribution).

There is an upper constraint on average farm stocking rates (averaged over the areas of grassland and fodder crops), of 2 LSU/ha, reflecting the enforcement of cross-compliance conditions designed to prevent overgrazing. A minimum stocking density of 0.5 LSU/ha is also enforced, to prevent under-grazing, again consistent with cross-compliance requirements to maintain grassland in good agricultural condition.

2.5 Intermediate products

The farm models also capture 'intermediate' products, i.e. crops and grass that are not 'traded', but rather support the production of other enterprises, especially livestock. For instance, livestock-feed equivalents of most crops can be produced, which are not sold off the farm, but provide ME availability for livestock enterprises. Feedstock equivalents of these same crops can also be produced to support the on-farm AD activity.

2.6 Purchased feeds

For the purposes of simplification, purchased feeds are not differentiated on the basis of all available types, but are limited to generic types: concentrates (based on an unspecified combination of cereals, fish meal, soya, etc.) and coarse fodder (i.e. a combination of various kinds of conserved grasses and some fodder crops), although both of these can also be produced on the farm (concentrates produced on the farm are in the form of 'straight' cereals). Purchased feeds are priced in the objective function at values prevailing in the reference year, i.e. 2009.

2.7 Crop rotations

The models include constraints on the relative proportions of cereals and oilseeds to break crops that can be grown (e.g. root vegetables, peas and beans, leys, etc.), reflecting rotational practice. These proportions are derived from actual practice for each of the farming systems being modelled (see Section 3.6 for more details).

2.8 Policy

The models are consistent with the policy environment prevailing in 2009 and this includes the reforms to the CAP introduced in 2003, i.e. the so-called Fischler reforms. The central tenet of these CAP reforms is the decoupling of support payments from production decisions through the introduction of a Single Farm Payment (SFP) paid on an area basis. UK payment rates will be calculated on a wholly regional basis by 2012. Receipt of this payment is subject to meeting certain minimum farming standards - commonly known as cross-compliance conditions, for example minimum and maximum stocking rates (the models reflect these stocking rate constraints).

Because payments by 2012 will be fully decoupled, economic theory indicates that they will no longer influence farm production decisions (although some economists argue that they may still do so in part). On the basis of this logic the value of support payments is not accounted for in calculating enterprise net margins. In the model,

\therefore, CAP support payments are ignored, as they provide no enterprise any relative advantage. Enterprise net margins are therefore based solely on market receipts.

2.9. Scenario run data requirements

Scenario modelling involves the manipulation of three aspect of the environment in which the farms operate:

(i) technology;
(ii) market conditions, primarily commodity and input prices;
(iii) the policy environment.

2.9.1 Technology change

In farm management terms, technology change may come in a number of forms:

(a) new management practices, tools or techniques;
(b) new plant or livestock technologies, i.e. cultivars and breeds;
(c) novel enterprises.

In this modelling exercise (a) and (b) are assumed to remain constant, but (c) is manipulated through the availability of anaerobic digestion as a diversification activity. Although it is likely that some changes in (a) and (b) might take place over the short term, this is not the focus of this modelling exercise, and so it is not necessary that technology change be modelled, only that both the scenario and reference runs be consistent in this regard.

2.9.2 Price change

Some of the modelling scenarios involve experimental changes in market conditions, including the prices of outputs and inputs. The reference runs of the two models are based on output and input prices prevailing in 2009, the most recent year for which official data were available. However, this price change scenario makes no assumptions about energy and input prices and so these are assumed to remain unchanged from the reference run.

2.9.3 Demand and supply change

Demand for agricultural commodities is not manipulated under any of the scenarios. The models are unconstrained under all scenarios with respect of supply (except in the case of milk) and so are free to vary supply volumes.

3. The arable and dairy farm type models

The sections that follow provide detail on the structure of the two farm type models. These will be treated separately where there are differences in approach, or use of data, between the two models, but where elements are the same, they will be outlined in common.

3.1. Farm structure

Arable farm

The arable farm model is based on an 'average' arable cropping farm located in the eastern counties of England. These farms typically produce cereals and other arable crops in simple rotations, often with continuous cropping with little or no pasture land. Farms are generally large, with large field sizes, high levels of mechanisation and relatively low labour input, unless horticultural enterprises are included. According to FBS estimates, the size of the average cereals-based farm in Eastern England was 311 ha in 2008. For our purposes, this has been rounded to 312 ha. There is no information readily available in published sources on number of fields within arable farms, so a notional number (12) was chosen for the model farm. For convenience, field sizes were standardised at 26 ha. This regularisation of field sizes is by no means a limitation, as the model is allowed to sub-divide fields, effectively creating any number of enterprise blocks.

Dairy farm

The dairy farm model is designed to represent a large specialist dairy farm based in the South East of England. These farms produce milk, but may also produce some beef from dairy offspring, usually cross-bred animals, or may sell young cross-bred calves on for finishing elsewhere. Land use is a mix of high intensity pasture with, on better land, cereals and maize grown for forage. Grassland is dominated by short-rotation leys, plus some permanent pasture, with perhaps a small area of rough grazing. On many farms the dairy herd is housed for a large part, or even all of the year, during which time they will be fed on concentrates and conserved forage, especially grass and silage maize. On the more efficient farms there is significant use of technology and IT, requiring high levels of capital investment. Dairy farms have a relatively high labour requirement compared to pure arable farms (except where horticulture is involved).

The dairy farm model is based on a real-world farm, i.e. the University of Reading dairy unit (Cedar). This farm consists of 610 ha in two separated blocks, stocked with 550 dairy cows, plus followers. The farmed area consists dozens of separate fields and field parcels, as registered in the 2009 IACS submission. In order to reduce the complexity of the LP model, these fields have been aggregated to 15, while maintaining the observed proportions of arable, leys and other grasses.

3.2 Farm labour

The arable farm

The model farm is provided with 660 man days of regular farm labour per year. This equates to one farmer plus two full-time hired staff, each working 220 days per year[2]. In practice, farm workers usually work more man days per year than this, so in reality the actual number of staff that this would represent would be less than 3. This labour availability figure is based on the amount of labour required, based on Standard Labour Requirements data[3], to run a farm of this size producing cereals and arable crops. In the real world some farms of this size might have more labour and some less, depending on the mix of enterprises on the farm and the use made of contractors. The annual labour requirements for all enterprises available in the model (based on Defra Standard Labour Requirements) are reported at Annex D. Beyond the level of farm labour available, additional labour is available through the purchase of contractor time.

Dairy farm

The dairy model farm is provided with 1925 man days of labour per year, i.e. this represents the farm manager and regular hired staff who, taken together, represent the equivalent of 7 full-time workers (i.e. each working 2200 hours per year[4]). In the real world, on a farm of this size, the actual number of man hours worked per worker could be more or less than 2200, depending on how much over-time is worked. The real world farm makes regular use of contractors and so the model also has this provision. Any labour required for farm operations (or AD) above the 1925 man days available is supplied by contractors.

3.3 Yields

Arable and dairy farms

As has been stated above, not all crop enterprises that might possibly be produced on these farm types are permitted, as there are a very large number of these and some, in the real world, are produced on a very small scale. Therefore, to reduce complexity, the model contains only the main agricultural crops, plus some representatives of the more minor crops, for example OSR but not linseed, or other minor oilseeds. Table 2 shows the list of crop enterprises available to both models. Note however that the arable model

---

[2] This labour figure is on the high side for a typical arable farm of this size (it is generally assumed that for pure cereals operations, one labour unit is required for every 300 ha. Nix, 2008). Additional labour is required if the farm carries root vegetables or potatoes. In this case, as the model needs to have access to a large range of potential feedstock supplies, and some of these, like potatoes, are labour intensive, additional farm labour has been provided.

[3] Standard Labour Requirements for various crop and livestock activities were derived from the Report to the UK Farm Classification Working Party, February 2004 (UKFCWP, 2004).

[4] 2200 hours equates to 1 Annual Labour Unit

is not permitted livestock enterprises, but is allowed to produce forage crops, including grass for silage for sale off the farm.

Table 2. Crop enterprises available to the arable and dairy farm type models, plus average farm yields

Crop enterprise	Average crop yield (seed, t/ha)	Yield of crop residues (biomass) (t/ha)	Whole-crop yields (t/ha)
Winter wheat	8.3	11.7	38.6
Winter barley	6.4	7.8	37
Winter oats	6.5	8.7	37
Other cereals (triticale)	6.0	4.5	31.3
Oilseed rape	3.4	-	46.2
Field peas	4.4	6.0	40.1
Field beans	3.8	6.0	50.7
Sugar beet	58.6	20	82
Potatoes (maincrop)	45.0	0	45
Maize (forage)	N.A.	0	45.4
Other fodder crops (fodder beet)	60.0	35.0	91
Field-scale veg (swedes)	75.0	20.0	95
Short-term ley (silage)	N.A.	N.A.	45.0
Permanent pasture	N.A.	N.A.	N.A
Rough grazing	N.A.	N.A.	N.A
Livestock	Milk yield (litres/year)		

Sources: Lang (2008); SAC (2008); Nix (2008)

Average crop yields have been derived from published farm management standards (see Sources above). Yields have been obtained for both the seed portion of the crop e.g. the grain, but also for crop residues and for the whole crop. Whole crop yields often do not equal the sum of seed and residues, because for feedstock (and forage purposes) whole-crop harvest is usually pre-ripe, where stems are still green and therefore more digestable. Data on crop residue and whole-crop yields are generally much more difficult to obtain than seed yields, because they are less often a commercial crop, and so the data used have in some cases been taken from field trials (rather than surveys of commercial operations), some of these from other EU countries.

3.4 Variation in yields across fields

Arable farm

A notional variation in yield per field over the model farm has been assumed, as a way of increasing the realism of the model. Field yield variation is shown in Table 3. For simplification purposes yields over the whole farm are symmetric i.e. weighted by area, they sum to 2.

Table 3. Notional yield variation by field in the arable farm type model

Field number	Land type	Area (ha)	Yield variation (as a proportion of field 1)
1	Arable	26	1
2	Arable	26	0.8
3	Arable	26	0.8
4	Arable	26	1.2
5	Arable	26	0.9
6	Arable	26	1.2
7	Arable	26	1.1
8	Arable	26	1
9	Arable	26	0.85
10	Arable	26	1.15
11	Arable	26	0.65
12	Arable	26	1.35

As indicated above, the model can produce crops either on whole fields (26 ha), or partition the field into smaller units in order to produce smaller areas of multiple crops. This is also true of the dairy model.

Dairy farm

Table 4 shows the 15 fields of the dairy model farm, together with their field sizes and notional yield variation. The proportions of arable, ley and permanent pasture seen on the real-world farm on which the model is based have been preserved in this field distribution. The area of rough grazing on the real-world farm is so small that for simplicity sake this has been designated as permanent pasture in the model.

The model can produce any crop enterprise available to it on the land designated as arable and can also bring all grass ley into arable cultivation (as this land is then part of the arable rotations). Permanent pasture is not typically brought into the arable rotation, but some of the higher yielding permanent pasture could be cultivated and to reflect this possibility the model is permitted to transfer 10% of this land to arable, although it does incur an additional cost, reflecting the soil improvement measures that may be required.

Table 4. Yield variation by field in the dairy farm type model

Field number	Land type	Area (ha)	Yield variation (as a proportion of field 1)
1	Arable	37.5	1
2	Arable	37.5	0.8
3	Arable	37.5	1
4	Arable	37.5	1.2
5	Arable	37.5	0.9
6	Arable	37.5	1.2
7	Arable	37.5	1.1
8	Arable	37.5	1
9	Ley	43.5	1.35
10	Ley	43.5	1
11	Ley	43.5	1
12	Ley	43.5	1.35
13	Perm. Pasture	42	0.65
14	Perm. Pasture	42	0.85
15	Perm. Pasture	42	0.8

3.6 Farm systems and rotations

Arable farm

Arable farms of this type operate a number of different rotations of different lengths, some involving fallow periods, others not[5]. For the purposes of this model a 6 year continuous cropping system has been adopted, with land rotating between cereals and various break crops. This type of rotation is fairly typical of arable farms in the Eastern Counties. Crop rotations are operated primarily to reduce pest and disease pressure (as well as, to a lesser extent, avoidance of the depletion of specific nutrients), which may built up over time if the same crop is continuously cultivated, or cultivated too frequently, on the same parcel of land. Under such a rotation, any crop that is not susceptible to the same diseases as cereals is considered a break crop, because these can be sown immediately following cereals and serve to reduce disease pressure on any cereals crops subsequently sown. In reality the pest and disease pressure at each farm site will vary, thus influencing the choice of crop in the rotation, but for this study Fusarium Head Blight on cereals, with consequent mycotoxin accumulation, is the driver in the choice of rotation restraints (Edwards, 2004)[6] .

[5] Set aside is voluntary at present and in the model the set aside area is assumed to be zero.
[6] Also considered important is control of Take-all root rot *Gaeumannomyces graminis.*

A typical 6 year rotation on this type of farm might be:

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
First wheat	Second wheat	Potatoes	First wheat	Barley	OSR

Because both the arable and dairy models are comparative-static, they cannot capture the whole rotation period and so reflect a snapshot within the rotation i.e. one rotation year. In the models therefore, a number of constraints are in place to capture these rotational limits as they might limit the combinations of crops that might appear in the notional 'average' year. So, for example, in any one year no more than 2/3 of the land on the model farms can be sown to either wheat+barley, or maize, or wheat+barley+maize combined. This means that in any one year, a minimum of 1/3 of the land must be sown to break crops. Restraints are also in place to ensure that no single crop can cover more than 1/3 of the farmed area and there are limits on the areas of field scale vegetables and potatoes such that the combined area can account for no more than 15% of the farmed area. In the case of potatoes, it is typical that the crop is not grown more often than once in 6-7 years on the same land for agronomic reasons[7]. Another factor constraining the area of potatoes and vegetables is labour availability. Both of these crops are very labour intensive and more significant areas of these crops would require a major change to the structure of the farm business, effectively changing the farm to a specialist vegetable producer. Because sugar beet and fodder beet are so similar in terms of disease vulnerabilities they are jointly restrained such that their combined area cannot exceed 25% of the farmed area, i.e. they can't be grown more often than one year in four.

Dairy farm

The dairy enterprise is assumed to be a self-contained Holstein-friesian herd, i.e. supplying its own replacements, with some pure-bred calves for replacements and some beef crosses. Pure-bred calves are reared outdoors and taken indoors 5 weeks before calving. Cross-bred beef calves (sired by a beef bull) are reared to 3 weeks and then sold to a rearer. Milking cows are housed all year round on sand bedding. The slurry is separated from the sand for storage and spreading. The replacements are grazed for half the year and spend the winter months indoors.

Milking cows can be fed on home-grown grass and maize silage, fodder crops, plus imported concentrate feeds and/or fodder. In the model, the feed requirements of dairy animals (in MJ of energy) are matched to feed supply on the basis of the nutritive value of various feedstuffs. The feed requirement of the average dairy cow is assumed to be 83,000MJ per year. Table 5 shows the nutritive values of a range of feedstuffs.

[7] To reduce in pest and disease pressure, particularly Cyst Nematodes and for soil structure reasons.

Table 5. Nutritive values of a range of feedstuffs per kg/t and per ha (where appropriate MJ/ha values are based on yields shown in Table 2).

Feed	Dry matter (DM) content (g/kg)	ME (MJ/kg DM)	ME (MJ/t FM)	ME (MJ/ha)
Wheat (grain)	860	13.6	11696	97077
Wheat (whole crop)	400	10.5	4200	162120
Barley (grain)	860	13.2	11352	72653
Barley (whole crop)	400	10.5	4200	155400
Oats (grain)	870	12.5	10875	70688
Oats (whole crop)	410	10.0	4100	151700
Other cereals (triticale)	860	12.5	10750	64500
Other cereals (whole crop)	410	10.0	4100	128330
Potatoes (maincrop)	210	13.3	2793	125685
Maize (forage)	300	11.0	3300	149820
Other fodder crops (fodder beet)	200	12.0	2400	144000
Field-scale veg (swedes)	105	14.0	1470	110250
Short-term ley (silage)	240	11.0	2640	118800
Permanent pasture	240	11.0	2640	89100
Rough grazing	240	11.0	2640	29700
Concentrate feeds (based on extracted soyabean meal)	900	13.4	12060	

Sources: Nix (2008); SAC (2008)
Note: Permanent pasture yields are notionally assumed to be 75% of leys and rough grazing yields 25%.
Note: Whole-crop wheat data is for whole-crop fermented.
Note: FM = fresh material; DM = dry matter.

The herd Calving Index is 397 (i.e. on average there is a 397 day interval between calvings). Dairy cows are culled, on average, after 3 lactations, and the herd replacement rate is 25% per annum. Making the assumption that it takes a minimum of 2 years to produce a replacement animal, there will need to be a heifer at 1-2 years for every milking cow in their final year (i.e. 3rd lactation) and an animal of 0-1 year for every milking cow in their second lactation. For a herd of 550 milking cows, this would mean the following replacements: 182 heifers of 1-2 years, plus 182 calves of 0-1 years. Table 6 calculates the nutritional requirements of these replacements, where livestock unit conversion ratios are used to estimate the nutritional requirements of replacements as a fraction of the nutritional requirements of a lactating dairy cow.

Table 6. Nutritional requirements of dairy herd replacements

Class of animal	Livestock Unit	Nutritional requirement (MJ/animal/year)
Calf 0 – 1 year	0.34	28220
Heifer 1 - 2 years	0.65	53950

Source: Nix (2008) and author's own calculations

In 2008/9 the real-world farm hosted around 200 ha of combinable crops (cereals/oilseeds) and 150 ha of forage maize; these crops were ensiled for forage. The remaining 260 ha were grassland (leys and permanent pasture). The real-world farm is approximated in the model, which has 300 ha of arable land and 300 ha of grasses, as shown in Table 4. The rotational practice differs on this farm to a wholly-cropped farm in that grass leys form part of the rotation. Under these conditions grass ley acts as another break crop for cereals and also for maize (which is grown extensively for forage). As with the arable farm, the rotational constraints mean that in any one year, a minimum of 1/3 of the arable/ley area must be sown to break crops, including grass leys – the area of permanent pasture is excluded from these restraints as it is fixed and not used in rotation with arable crops. Other restraints on areas of single crops follow the approach set out for the arable farm.

3.7. Fertilizers

The fertilizer requirements of each crop are specified in the models in terms of N, P and K separately. Published standards (Nix, 2010; SAC, 2009), reflecting common commercial practice, have been used to estimate the N, P and K growing requirements for each crop. These nutrient requirements must be met each year by fertilizer applications, where these represent a top-up to the nutrients present in the soil, carried over from the previous year. Fertilizers can be supplied from one of three sources, purchased inputs, slurry from dairy animals, or from AD digestate, where the latter two are available. The nutrient requirements for each crop are shown in Table 7. The nutrient supply available from digestate is given in section 3.11.

Table 7. Nutrient requirements of crops in the arable and dairy farm models

Crop enterprise	Nitrogen (N) (kg/ha)	Potassium (K) (kg/ha)	Phosphate (P) (kg/ha)
Winter wheat	200	70	70
Winter barley	180	70	70
Winter oats	120	60	60
Other cereals (triticale)	180	70	70
Oilseed rape	210	40	40
Field peas	0	50	40
Field beans	0	50	40
Sugar beet	100	75	50
Potatoes (maincrop)	220	250	150
Maize (forage)	130	140	50
Other fodder crops (fodder beet)	125	150	60
Field-scale veg (swedes)	80	125	125
Grass silage (Ley and permanent pasture)	220	150	90
Rough grazing	0	0	0
Fallow	0	0	0

Source: SAC (2008).

3.8. The AD unit

3.8.1 Size / capacity

The model is permitted to adopt an AD activity at any scale up to a digester output capacity of 500 kW continuous – in terms of farm-based digesters this would be loosely termed 'med-large'. This constraint is relaxed in some scenarios. Allowing for some down-time a digester of this size, run for 8322 hours per year (347 days), would generate, at 35%[8] conversion efficiency, 4,895,000 kWh of electricity[9] from an output of 1,398,655 m^3 of methane per annum. The model is free to select any scale up to this maximum of 500 kW, based on:

- the availability of farm resources (e.g. spare labour)
- the availability of feedstock (this will be constraining when the model is not permitted to import feedstock onto the farm)
- the contribution of the AD activity to the farm net margin

[8] Some modern CHP equipment generates electricity, it is claimed, at up to 40% efficiency. However, efficiency rate is, in part, related to scale and as the model has to allow for much small digester capacities than 500kW, a slightly more conservative estimate is used.
[9] This would power approximately 630 homes.

3.8.2 Capital cost

The capital costs incurred in the establishment of the AD unit will vary according to the scale of the digester adopted by the model and the particular technologies required. Data on digester establishment costs are available from a number of commercial sources, but these vary considerably due to differences in the type and complexity of the system, the quality of the materials used and the amount of ground work (sometimes called civils work) that has to be done before installation. Another factor causing variation in costs is the extent to which the ground work can be carried out by the farm's own labour. For illustration purposes capital costs are provided (see Table 8) for the maximum permissible digester size (500 kW) and a range of sizes below that. These costs are based on German data, and indicate a capital cost of establishment of £2,072 per Kw for the 500 Kw digester. Using the illustrative data given at Table 8 as a guide, and using an exchange rate of 1 Euro = £0.893824 (exchange rate on 11/11/09) the total establishment cost of a 500 kW AD unit would be £926,000[10].

Table 8. Illustrative AD unit establishment costs for a range of digester sizes (thousand Euros)

Digester capacity	55 kW	150 kW	220 kW	500 kW
Basic equipment				
Substrate processing	22.1	37.2	43	32.5
Fermenter	94.5	113	320	300
CHP unit (incl grid connection)	65	178	206	362.5
Gas flare	12	25	25	25
Peripheral equipment				
Co-substrate preparation			35.4	80.5
Crop preparation pre-digester		27.5	32.5	37.5
Additional fermenter (with cover)	29.2	32	45.8	104
Total of basic and peripheral	222.8	412.7	707.7	942
Planning (+10%)	22.3	41.3	70.7	94.2
Total investment	**245**	**453.9**	**778.5**	**1036.2**

Source: Adapted from Anon. (2006) Handreichung - Biogasgewinnung und nutzung. Gülzow, Germany, Fachagentur Nachwachsende Rohstoffe e. V.
Note: the data above do not include the cost of a pasteurisation unit.

Available data from suppliers of AD plant in the UK, suggest that AD capital costs are rather higher in the UK than in the rest of Europe. Andersons (2008) suggest that capital set up costs in the UK vary between £2.5k and £6k per Kw of digester capacity, depending on the scale of the unit installed and its complexity, while British Biogen (2003) suggest a cost range of £3K to £7K per kW. As the minimum figure quoted by Andersons is higher than the value in Table 8 this confirms the industry view that continental data underestimate the costs likely to be incurred in the UK. Köttner, *et al.*

[10] For comparison purposes, Yeatman and Jefferies (2009) reported establishment costs for a 370 kW AD unit on Yeatman's Devon farm at £1.05M.

(2008) report the cost of establishing a 500 kW unit in the UK in the year of publication of £1.36M, equating to £2,720 per kW, while Yeatman and Jefferies (2009) report capital establishment costs on a 370 Kw AD unit of £2,838 per kW, both of these estimates lying at the low end of the Andersons range.

Assuming that all capital costs were borrowed, and assuming loan repayment over 10 years, average repayment charges at 4% interest on borrowing of £1.5M would be (capital repayment - £150,000 + interest - £35,100) £185,100.

On a purely arable farm using crops as feedstock, it would also be necessary to construct a silage clamp to store the ensiled crop. SAC (2008) estimates the cost of constructing a clamp with concrete walls and floor at £60 per tonne of silage storage capacity. Assuming that the feedstock was a mixture of maize and grass (produced from equal areas), a 312 ha farm would generate 14,102t of fresh material (assumed to be half maize and half grass). Ensiled this total would reduce to 8400t and the silage clamp would therefore cost approximately £0.5m. The interest charge, plus capital repayment, for this additional capital outlay, on the same terms as above, would be £61,500. The dairy farm would already have a clamp of this capacity and so would not incur this type of capital cost to set up an AD unit. The capital cost of a digestate storage unit has been included in the capital cost of the establishment of the AD plant itself.

The cost of installing a digester on a per kW basis is seen to fall with increasing unit size, in large part because some of the costs incurred are relatively inflexible and are incurred in similar amounts regardless of unit size. These costs are those associated with obtaining planning permissions, consultancy and advice, grid connection and infrastructure work etc. It has been assumed for modelling purposes, perhaps somewhat heroically, that these costs would amount to around £200k, i.e. costs of around £200k would be incurred for these items, regardless of the scale of the unit installed. This ‘fixed’ element of capital costs has been reflected in the estimation of capital costs included in the model and results in the declining marginal capital cost data shown in Table 9.

Table 9. Capital cost of AD installation reflected in the model, on a per kW basis, at a range of AD unit sizes (includes cost of silage clamp)

AD unit size (kW)	Total capital cost (£M)	Capital cost per kW (£)
50	0.4	8,000
100	0.57	5,700
200	0.94	4,700
300	1.29	4,300
400	1.64	4,100
500	2.0	4,000

3.8.3 Running costs

Little published data is available on the running costs of a farm-based AD unit in the UK because there are very few units currently operating, and the estimates that are available vary very considerably due to differences in technical specification. Table 10 shows a range of costs based on data drawn from a number of sources. Because these data are derived for AD units of different sizes, they have been re-based pro-rata to equate with a unit of 500 kW output capacity.

3.8.4 AD labour costs

Based on experience in Germany, Köttner, *et al.* (2008) assume a labour requirement of 4-5 hours per kW, or 2000 hours per annum (5.5 hours a day) for a 500 kW unit. The Köttner, *et al.* labour estimate is set at a relatively high level due to the assumption that the digester in their case study was taking poultry manure as a feedstock and also because of the use of multiple feedstock sources, requiring high levels of feedstock mixing activity. Also, based on German data, FNR (2009) report labour requirements of between 3 and 7 hours per kilowatt, depending on digester size, and an average of 4 hours per kilowatt for a 500 kw unit. Andersons (2008) provide a range of labour requirements for the UK from 1 hour per day for simple systems using single feedstocks, to complex systems requiring 2-3 full time staff per day. Greenfinch (2009) assume staff operating costs for a digester in this size range of £18,000, while Yeatman and Jefferies (2009) report labour costs of £10,800 on a 370 kW unit, rebased to £14,600 for a 500 kw unit. For modelling purposes it is assumed that a minimum level of labour is required regardless of the scale of the AD unit. In the model, a minimum of 500 hours per annum is required whenever AD enters the model solution and therefore this requirement increases linearly from this base with the scale of the activity at a rate of 3 hours/kW p.a. For a 500 kW AD unit therefore, the labour requirement would be 2000 hours p.a.

3.8.5 Maintenance costs

Köttner, *et al.* (2008) estimate maintenance costs as a percentage of capital costs, with different rates applied to different parts of the AD plant. The highest of these rates is 3.2% of capital costs and this applies to maintenance of the CHP unit. Andersons (2008) suggest maintenance costs at 1-2% of capital costs and based on this data the NNFCC in their Biogas Calculator assume costs for the digester of 1% and 1.5% for the power generation unit (NNFCC, 2009). Yeatman and Jefferies (2009) suggest an implied maintenance costs rate of 2.8% of capital costs.

3.8.6 Insurance costs

A common convention in farm management accounting is that insurance costs for plant and equipment can be estimated at 1.5% of capital costs. This convention appears to have been followed by Köttner, *et al.* (2008) in estimating AD insurance costs. However, Andersons (2008) argue that the additional insurance burden of the AD unit may be small, because claims are rare, and that in some cases the existing farm insurance policies could be extended to cover it.

3.8.7 Electricity

Köttner, *et al.* (2008) indicate a range of electricity requirements for AD depending on the size and type of digester, from 9.1% of electricity generated for a 100kW unit to 7.7% for a 500 kW unit. No electricity should be required to heat the tanks, but rather, power is required for mixing and chopping of feedstocks, stirring of tanks, operation of pumps etc. Taking the 500 kW figure, electricity costs under the Köttner, *et al.* (2008) assumptions, would be £24,000 p.a. (based on an assumed 3,507,550 kWh electricity generated, and 270,080 kWh electricity used by the digester plant at 9 pence per kilowatt). Andersons (2008) do not report electricity costs, merely assuming these to be 'small'.

Table 10. Various estimates of digester running costs (£ per annum) based on a 500 kW unit.

Cost item	Greenfinch / Andersons	Yeatman	Köttner et al.	Model assumptions
Labour	18,000	14,600	29,940	18,000
Maintenance and repair	30,000	39,200	43,800	37,500
Insurance		21,300	20,400	15,000
Electricity			39,000	39,000
Other costs			11,500	15,000
Total	48,000	114,100	144,640	124,500

Note: 'Other costs' as modelled follow Köttner, *et al.* (2008), who assume these to be 1% of capital costs, based on purchase anti-foaming chemicals, expert advice, laboratory testing of samples, pH measurement equipment, removing problematic substrates, additional storage during digester failure etc.
Note: Model labour costs based on an assumed 2000 hours of labour input at £9/hour[11]

3.8.8 The model cost assumptions

The model cost assumptions are given in Table 10 and are based on a 500 kW digester costing £1.5M[12] (£3k / kW), requiring 4 hours of labour time per kW due to the potential use and mixing of multiple feedstocks and with the following additional cost assumptions: insurance - 1% of capital cost; maintenance - 2.5% of capital cost; 270,000 kW of electricity required to run the AD plant and 'Other costs' at 1% of capital costs. It is assumed in the model that all electricity generated is exported off the farm and that the electricity used to run the digester plant comes from the mains supply.

[11] Defra report (Defra, 2010a) that the average earnings per hour of a full-time male farm employee in the 12 months to September 2009, was £8.19. Nix (2008) reports additional employer costs were: Employers National Insurance contribution at an additional 12.8% of basic salary; plus Employers Liability Insurance at 1% of basic salary (see Annex A).
[12] This excludes the cost of a silage clamp, which in the case of the arable model adds a further £0.5M to capital costs.

The model is constructed to require a minimum labour component for the AD unit regardless of scale, equating to one hour a day of labour time. Beyond this one hour, additional labour is added (using a linear relationship) in proportion to the increase in scale of the unit, up to 5.5 hours a day (2000 hours a year) for a 500 kW unit.

3.9 AD Feed-stocks

In most of the scenario runs AD feedstocks are derived solely from the crops that can be grown on the farm, plus, for the dairy farm only, any animal slurry that is produced. The model may produce crops for sale while diverting crop residues (leaves and stems) from these same crops to the digester, or crops may be grown specifically for the digester and harvested whole-crop (sometimes semi-ripe) and ensiled for storage. Under some scenarios feedstocks can be imported onto the farm (see Sections 5.5 and 6.5 for more details).

3.9.1 Methane yields of crops

Table 11 shows methane yields for all of the crops available to the models, both for seed, crop residues (where this data is available) and for the whole-crop. The table presents methane yields per tonne of fresh material (FM). Whole-crop harvest often takes place before crops are fully ripe and consequently not only are these green crops more digestable as fodder, but because biomass yields are higher, methane yields are also higher on a per ha basis.

Table 11. Methane yields for crops and slurry (m^3 per t FM)

Crop enterprise	Methane yield of seed (m^3/t FM)	Methane yield of crop residues (m^3/t FM)	Methane yield of whole (green) crop (m^3/t FM)
Winter wheat	298	142	125
Winter barley	307	125	82
Winter oats	307	213	76
Other cereals (triticale)	307	213	110
Oilseed rape	285	253	50
Field peas	-	254	47
Field beans	-	254	47
Sugar beet	71	34	81
Potatoes (maincrop)	27	0	27
Maize (forage)	232 (grain)	164	99
Other fodder crops (fodder beet)	42	34	74
Field-scale veg (swedes)	42	31	74
Grass silage	74	74	70
Slurry	N.A.	N.A.	13

Source: Salter (2009).

3.9.2 Methane yields of cattle slurry

The average dairy cow, fed on a typical diet of concentrates and grass (silage or hay) produces around 19.2 t of slurry per year, while a maturing animal (herd replacement) produces, on average, 11.6 t (MAFF, 2000). Cattle slurry has a methane yield of 13 m^3 per t of fresh material because of the modelling assumption that the replacement animals are only housed for half the year, only half of their slurry output will be available for the AD unit.

3.10 AD outputs

The output of the digester is biogas (it is assumed that about 60% of the biogas is methane, with the bulk of the remainder being CO2). The model assumes that the biogas is burned in a CHP unit to produce electricity, which is sold to the national grid (grid connection charges are thus accounted for). The sale of biogas was considered impractical in view of the present state of development of the market in the UK, particularly the lack of infrastructure for injection of biogas into the gas grid. It is assumed that no use is made of the heat generated (it is rare for heat from farm-based CHP to be used for commercial purposes), so this is assumed to be vented to the atmosphere, although some will be used to heat the digester tank.

Estimating the market value of the electricity is not straightforward, because there are a number of possible selling options for the farmer wishing to maximise the return for this product. First, the electricity could be exported off the farm under the guaranteed export price arrangement. In this case, the electricity would return 3 pence/kWh (this price is guaranteed for 20 years index linked). Alternatively, the farmer could opt out of this arrangement and sell at prevailing market price[13] which in turn will depend on market conditions and the deals available from the electricity suppliers. Another option would be to use the electricity on the farm and offset this against electricity purchases from the grid. The value of doing this to the farm business would again depend on the prevailing price of business-rate electricity. As likely returns, or savings, in the latter two cases are unknown, it is assumed that the first of the options is chosen, i.e. that electricity is exported off the farm under the fixed export price arrangement.

A feed-in tariff is also available for the same period of £0.115/kWh, this being available on electricity generated (whether exported to the grid or not) from on-farm AD units at 500 kW or less. Total receipts for electricity generation are thus £0.145/kWh. The renewable heat incentive was not available at the time of modelling so no account is taken of this as a potential source of revenue.

[13] Under this scheme it is possible to opt out of the export price agreement, on an annual basis, and receive the prevailing market wholesale price for electricity.

3.11 Digestate

3.11.1 Nutrients from digestate derived from crops

In the models the digestate from the AD unit is made available as fertilizer for use in the production of crops. It is assumed that the digestate supply from the previous year is the same as the supply in the current year. The nutrient value of the digestate is dependent on the crops/residues that go into the digester as feedstock and so the model is set up to change the nutrient value of digestate on this basis. Nutrients are assumed to remain unaltered by digestion, and so the nutrient values of the digestate remain unchanged from the nutrients present in the crops going into the digester.

Data on the nutrients present in different types of agricultural crops are available from Maff (2000) and KTBL (2002). These estimates are based on laboratory assays and are therefore direct measurements, rather than estimates. However, there are a number of problems with using these data in this context. First, no Maff (2000) data are available for Nitrogen levels in different plant material (see Annex C). Second, the KTBL data are based on measurements taken in Germany, where soil conditions and agronomic practice may differ from the UK. Third, it is known that levels of nutrients in plant material vary according to the soil nutrient conditions and this in turn is affected by past and current nutrient application rates. The nutrient application rates (Kg/ha) deployed in this modelling exercise may, to greater or lesser extent, be very different from the field-level nutrient application rates generating the plant nutrient levels reported in Maff (2000) and KTBL (2002). For the above reasons, it was decided that, in the model, the assumptions about the nutrient levels present in the crops grown should be based in some way on the field-level application rates actually used in the model.

The levels of nutrients applied to growing crops are based on the principle of 'top up'. Soils have variable levels of background nutrients according to soil type, rainfall, soil organic matter and previous cropping history. Nutrient application levels are determined as those necessary to replace losses due to leaching and removal of plant material from the field at harvest. Broadly speaking therefore, after deducting for leaching, the 'top up' represents the amount of nutrients contained in the plant material removed from the land at harvest. Commonly, at harvest, seeds and grain are removed and the remaining plant material is chopped or mulched and returned to the land. The nutrients contained in this mulched plant material will therefore become available in the soil through bacterial action over time. The top-up amount therefore relates to the loss of nutrients in the seed or grain. Where the whole crop is taken, as in the case of maize silage, nutrient losses are higher and so higher levels of 'top up' are required. In the model, all crops grown specifically for the digester are assumed to be harvested whole-crop. Another factor that needs to be taken into account is the proportion of the plant that remains in the ground post harvest, i.e. the lower stem and the roots. This residual portion of the plant will also contain nutrients. This proportion varies from species to species and between plants within a species, with no residual where root crops are concerned, but for other crops, such as cereals and oilseeds the proportion has been fixed at 25%.

P and K are known to be very stable in soils (Soffe, 1995) and so losses of these nutrients to the environment are assumed to be zero. Losses of N, particularly through leaching, can be high, for example where N is applied to crops without a well established root network, or when there is heavy rainfall. In the case of this modelling exercise loss of N from the soil to the environment has been set at 15% (Bockman, *et al.*, 1990).

The levels of nutrients per tonne of plant material can thus be calculated for Nitrogen as:

$(NA_i * (1/LR) * HP_k) / Ywc_i$
Where:

NA = nitrogen application rate / ha for crop **i**
LR = average nitrogen leaching rate (15%)
Ywc = yield of crop (whole crop) or crop **i**
i is crop type (all crops)
k is crop type (non-root crops)
HP = harvested proportion of the whole crop (e.g. 75% for the **k** crop types)

Any difference between the nutrients available through use of the digestate and the nutrient requirements of the growing crops is made up by fertilizer purchases. Table 12 shows the nutrient (N, P and K) values of the various crops which might be used as feedstock, expressed as kg per tonne of crop (whole crop).

Table 12. Nutrient content of crops used as AD feed stocks (kg / t of whole crop)

Crop enterprise	Nitrogen (N) (kg/t whole crop)	Potassium (K) (kg/t whole crop)	Phosphate (P) (kg/t whole crop)
Winter wheat	3.3	1.3	1.3
Winter barley	3.1	1.4	1.4
Winter oats	2.1	1.2	1.2
Other cereals (triticale)	3.7	1.7	1.7
Oilseed rape	2.9	0.7	0.6
Field peas	3.7	0.9	0.8
Field beans	2.9	0.7	0.7
Sugar beet	1.0	0.8	0.5
Potatoes (maincrop)	4.1	4.7	2.8
Maize (forage)	1.8	2.3	0.8
Other fodder crops (fodder beet)	1.2	1.4	0.6
Field-scale veg (swedes)	0.7	1.1	1.1
Grass silage	3.1	2.5	1.5
Fallow	N.A.	N.A.	N.A.

Source: authors own calculations.

In the case of peas and beans, because these legumes fix atmospheric nitrogen in the plant material, there is no external N application in that crop year and so it is assumed that there is no N leaching from the soil. Peas and beans fix about 200 kg of N per ha per year in plant material (Fried and Broeshart, 1975)

As a means to validating the values provided in Table 12, Annex C shows equivalent estimates of nutrient levels present in whole crops, as provided by Maff (2000) and KTBL (2002). If the model values are valid, there should be reasonable correspondence with the values in the published sources, as indeed there is. There is very close correspondence between model assumptions for nutrient levels in crops and published values for both nitrogen and phosphorous, but the correspondence for potash is not so good. However, there is also considerable variation between the Defra and KTBL sources on this particular measure, suggesting some systematic difference in soil potassium levels, or application rates between the sources. In the case of the potassium (k) values provided by KTBL, to achieve crop concentrations at the levels indicated, per ha application rates would have to be more than double common agronomic practice in this country.

3.11.2 Nutrients from digestate based on animal slurry

The dairy unit generates nutrients in the form of manures and slurries. These may be applied directly to land or used as feedstock in the AD digester. The nutrient value of cattle slurry is estimated in Table 13, which shows available nutrients excreted for different classes of dairy animal, assuming a typical diet of concentrates, plus hay or grass silage.

Table 13. Available nutrients excreted per week and per year by type of dairy livestock.

	Kg per week			Kg per year		
Type of animal	N	P	K	N	P	K
Dairy cow	0.81	0.44	1.33	42.12	22.88	69.16
Young cattle (250 kg)	0.27	0.12	0.36	14.04	6.24	18.72

Sources: Adapted from SAC (1992).

When the AD unit is operating, it might be an issue that there is insufficient land to take the nutrients supplied and still stay within agronomic guidelines for crop and grass nutrient requirements. This is a real possibility in the case of livestock farms, where nutrients are invisibly imported onto the farm in the form of animal feeds, especially concentrates. The model is not permitted to apply more nutrients (including those sourced from digestate) than is optimal for the crops being grown.

4. The scenarios

In selecting the scenarios to be modelled there were a number of givens. Under all scenarios the farm type models would be required to maximise farm net margin. The choice of the LP modelling approach obviated the need to design scenarios to explicitly explore the issue of digester scale, because the model's freedom to adjust digester scale according to the availability of resources and feedstocks means that the digester scale issue is explored automatically. Given the above, a suite of scenarios were selected to explore the implications for AD uptake and scale of operation of changes to various states of: the market for electricity; agricultural commodity prices; availability of feedstocks and the energy policy environment. Four basic scenarios were identified, within which a number of subsidiary scenarios were selected.

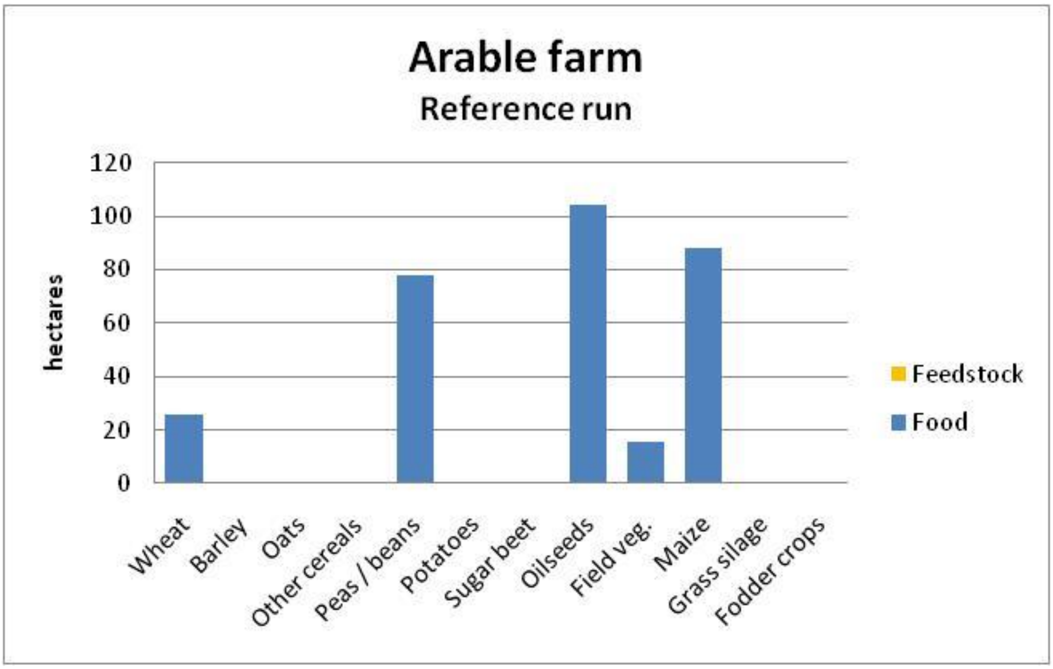
- Farming objectives (Scenario 1)
    - Maximize profit
- Market conditions (Scenario 2)
    - Higher commodity prices
    - Higher energy prices
- Government policies (Scenario 3)
    - variation to level of feed-in tariff
- Importation of feedstock (Scenario 4)
    - Forage maize or other ensiled crops, plus slurry
    - Food waste

5. Model results – arable farm

5.1 Reference run

The reference run represents the operation of the arable farm with no AD activity available. The reference run serves two purposes. First, it provides a means of validating the model, by comparison of modelled outcomes with real-world expectation. Second, it provides a comparator for scenario 2, where the AD option is introduced, allowing the marginal changes in farm operations arising from AD to be identified. In this case the model produces a fairly typical cereals-arable rotation of with about two-thirds of the farm under maize and combinable crops and one third under break crops, particularly field peas and beans (see Figure 1). The reference run outcome is slightly a-typical of cereals rotations, in having a fairly low representation of cereals, but in this instance the model is reacting to the market prices available in 2009 in order to maximise returns. In 2009, cereals prices were relatively low, especially compared to the previous year, and oilseed prices were high relative to cereals. In the real world farmers would not know current year prices and would make planting decisions on the basis of previous years' prices and the constraints of their ongoing rotation. This tends to smooth out extreme fluctuations in the planted area of individual crops, although this particular distribution of crops is perfectly feasible and could occur in a single year in a cereals-based rotation, where the cereals area would be higher in other years.

Figure 1. Arable farm – reference run results



The nutrient application rates in the reference run are shown in Table 7, where it can be seen that the model imports around 80t of fertilizers, half of this being nitrogen; at a total cost of £51.7k. Under the reference scenario farm net margin is £82,995[14].

5.2 Scenario 1 – AD: maximisation of farm net margin

The first scenario run maintains all of the conditions pertaining to agricultural commodity production seen in the reference run (policy, market, technology, etc.), but adds the option of an AD activity based on current renewable energy price and policy settings, i.e. electricity price, value of feed-in tariffs, regulatory environment etc. Under this scenario the model is again tasked maximizing the farm net margin.

When AD is introduced to the model, it is taken up as an activity at a digester scale equivalent to a 495 kW (electricity output). The feedstock for this digester comes largely from 78 ha of sugar beet, harvested whole-crop and 104 ha of wheat, also harvested whole-crop. Three crops are produced for sale as food and livestock feed, these being peas and beans, oilseeds and field-scale vegetables. Vegetables provide good margins per ha, and are produced on that basis, while the peas and beans and oilseeds crops are used as breaks in the cereals rotation, as well providing crop residues for the AD unit. Under this scenario, the former emphasis on food crops has been replaced by an emphasis on provision of feedstocks for the digester. It is interesting to note that the crop that is most commonly grown as feedstock for the small number of farm-based AD units operating in this country, i.e. ensiled maize, does not feature. Analysis of the net margins obtainable on this crop, compared to whole-crop wheat and sugar beet (see Annex B) reveal why this is the case, i.e. both whole-crop wheat and sugar beet yield higher methane values per ha than maize and offer higher enterprise net margins when used as feedstocks.

Nutrient application rates for this scenario are shown in Table 14, where comparison is made with the reference run. As can be seen, this scenario results in savings in all nutrient purchases, especially in the case of nitrogen, which falls 53%, and potassium, which falls almost 60%. These reductions in nutrient purchases are in great part due to the cycling of digestate from the sugar beet and wheat crops back onto the land, but also due to the elimination of maize from the cropping pattern, this having a high potassium requirement.

[14] The average net margin for this type of farm in 2008 according to the FBS (the latest year for which data are available) was £72k.

Figure 2. Arable farm. Scenario 1 (AD: max farm net margin) results.

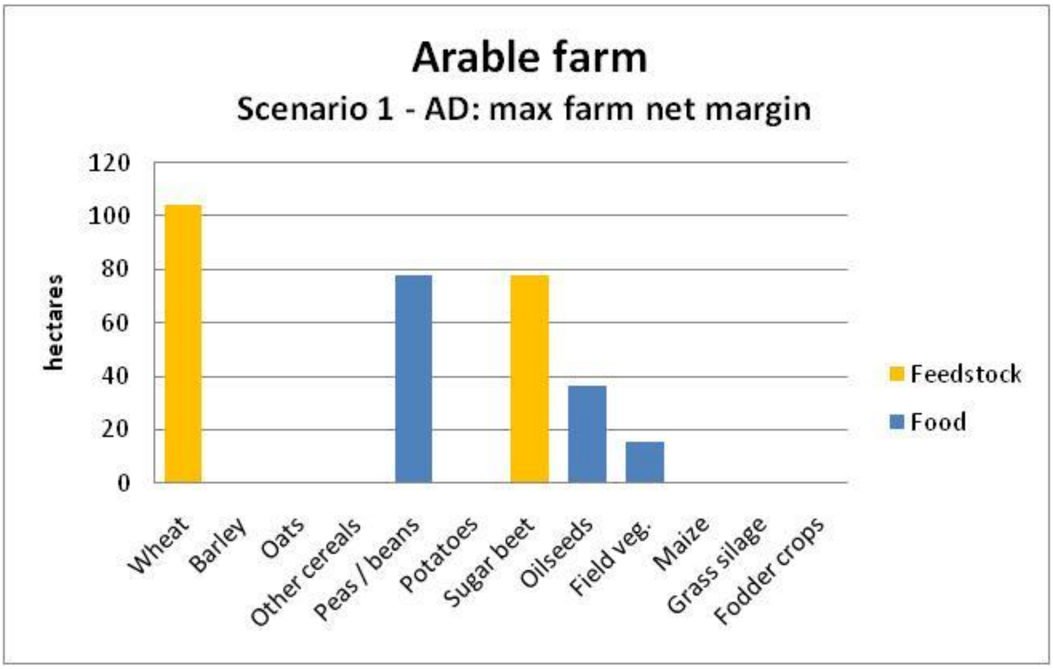


Table 14. Whole-farm purchase of nutrients under the reference run and scenario 1.

	Reference run (kg)	Scenario 1 (kg)	Percentage change
Nitrogen (N)	39,796	18,387	-53.8
Potassium (k)	24,185	9,768	-59.6
Phosphorous (P)	15,467	9,359	-39.5

Labour use under the reference run is 496 man days (2.3 man years assuming 220 days worked per year) and this rises with the introduction of AD to just under 600 man days, plus an additional 87 man days of contractor time. This increase is only in part due to the labour requirements of the AD unit itself, with additional labour also required because of the introduction of sugar beet crop - this being a very labour intensive enterprise.

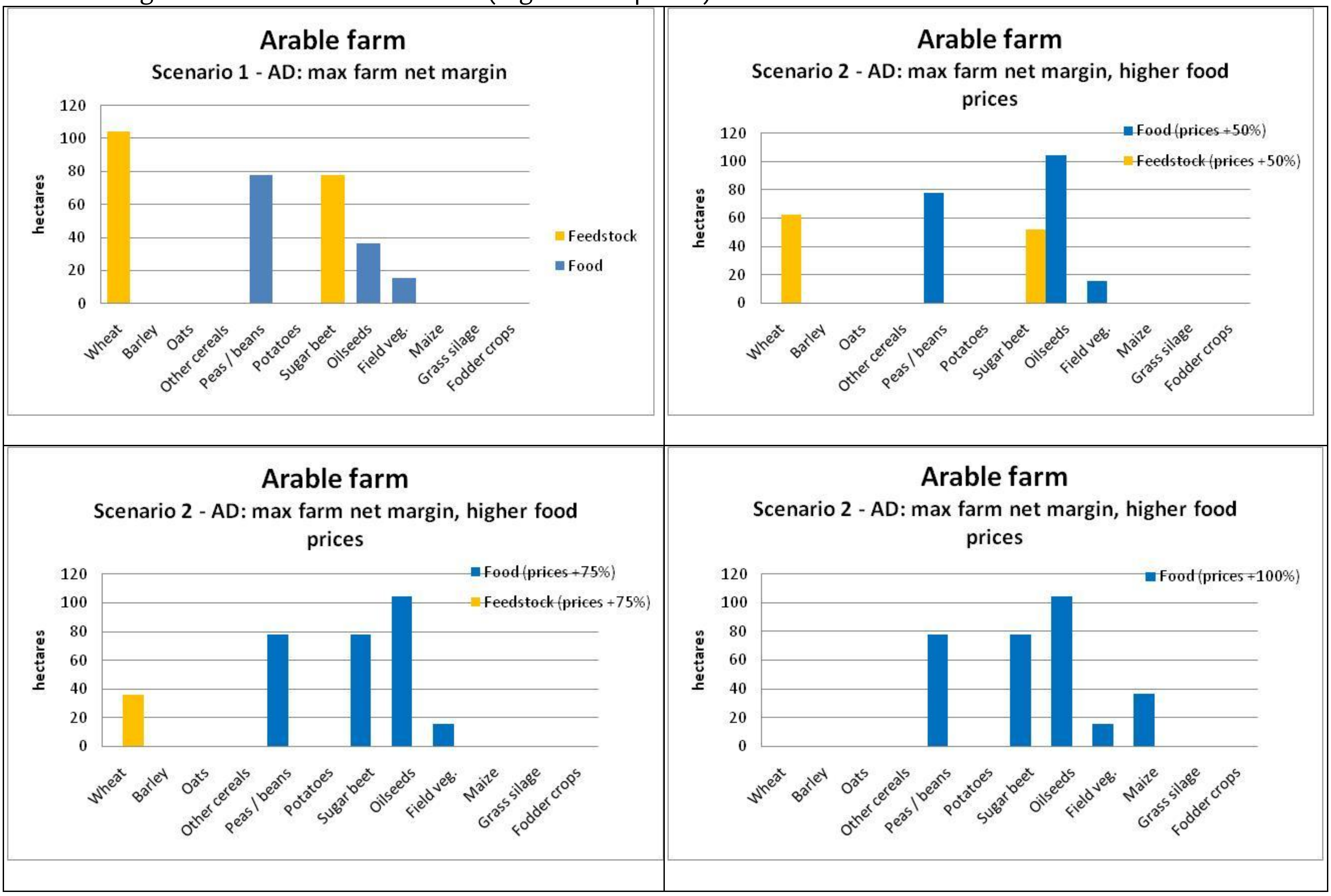
Under scenario 1, farm net margin is £258,559, a 212% increase on the reference run. The AD activity has thus added £175,564 to the farm net margin.

5.3 Scenario 2 – higher commodity prices

In this set of scenario runs, the general conditions applying in scenario 1 are carried over, but food and feed prices are increased in stepwise fashion until changes in the operation of AD on the farm are observed. Price increases are applied uniformly across all commodities, with step 1 introducing a 25% increase in prices and step 2 a 50%

increase and so on. The simplifying assumption is made that input prices remain unchanged, as does the export price for electricity. This scenario is designed to explore the competitive position of AD in relation to food and feeds production and, in particular, identify the price thresholds at which AD becomes uncompetitive. Using the scenario 1 results as a point of reference, a 25% increase in food and feeds prices generates no changes in the size of the AD operation, or the pattern of feedstock production. With price increases at 50% however, some changes are evident, as shown in Figure 3.

Figure 3. Arable farm. Scenario 2 (higher food prices) results



As Figure 3 shows, with a 50% increase in food and feed prices the area of crops produced for feedstock, both wheat and sugar beet, contracts, but some production remains. Under this scenario, land is transferred into production of oilseeds for food, to take advantage of much improved margins under this enterprise. With prices 75% higher than the 2009 base, the area of feedstock production contracts to just 36 ha (whole-crop wheat), with the greater part of remaining digester feedstocks coming from residues from the peas and beans, sugar beet and oilseeds crops. With food and feed prices double those in 2009, production of AD feedstocks ceases, but the AD unit continues on the farm, fed solely by crop residues. The pattern of crop production under this price regime is similar to the reference run, except that the small area of cereals and half the area of maize gives way to sugar beet.

Nutrient purchases under these price scenarios are shown in Table 15, where it can be seen that purchases are unchanged from scenario 1 under the 25% price increase, but that the scale of the savings begins to decline once price increases hit 50%. At this level of price increase N purchases increase 54% compared to scenario 1, though the increases in P and K are rather more modest. By the point of a doubling in prices, little if any of the N purchase savings seen under scenario 1 remain and P purchases are actually 123% higher, making them 35% higher even than under the reference run. The savings in K purchases seen under scenario 1 seem rather more resilient however, in part due to the low potassium requirements of the oilseeds crop, which comes to dominate the cropping pattern under all of the high price increase scenario runs.

Table 15. Whole-farm purchase of nutrients under the reference run and scenario 2.

	Scenario 1 (kg)	Scenario 2 – prices +25% (% change)	Scenario 2 – prices +50% (% change)	Scenario 2 – prices +75% (% change)	Scenario 2 – prices +100% (% change)
Nitrogen (N)	18,387	0	+54	+88	+95
Potassium (k)	9,768	0	+11	+46	+54
Phosphorous(P)	9,359	0	+21	+80	+123

Labour use under all of the price increase scenarios is higher than under the reference run, but from 50% onwards, labour use is lower than under scenario 1. More specifically, use of on-farm labour is unchanged but the use of contractors disappears. With price increases at 75% some on-farm labour use is also eliminated, but with a doubling of prices use of on-farm labour is almost entirely restored to scenario 1 levels due to the replacement of crops, in the cropping pattern, with low per hectare labour requirements (such as wheat and maize) with crops such as sugar beet where labour requirements are much higher.

Table 16. Labour requirements on the specialist cereals farm in the reference case and under scenario 2.

	Scenario 1 (man days p.a.)	Scenario 2 – prices +25% (man days p.a.)	Scenario 2 – prices +50% (man days p.a.)	Scenario 2 – prices +75% (man days p.a.)	Scenario 2 – prices +100% (man days p.a.)
Farm labour requirement	597	597	597	567	591
Contractors	87	87	0	0	0
Total farm labour requirement	684	684	597	567	591

As can be seen in Table 17, farm net margin is higher under all of the scenario 2 runs than both the reference case and scenario 1, due to higher food and feed prices. As the contribution of the AD unit to net margin declines, the effects of higher food and feed prices compensate. With a doubling of food and feed prices the AD unit is only a fraction the size it was under scenario 1, but due to better returns from commodity sales farm net margin is 70% higher.

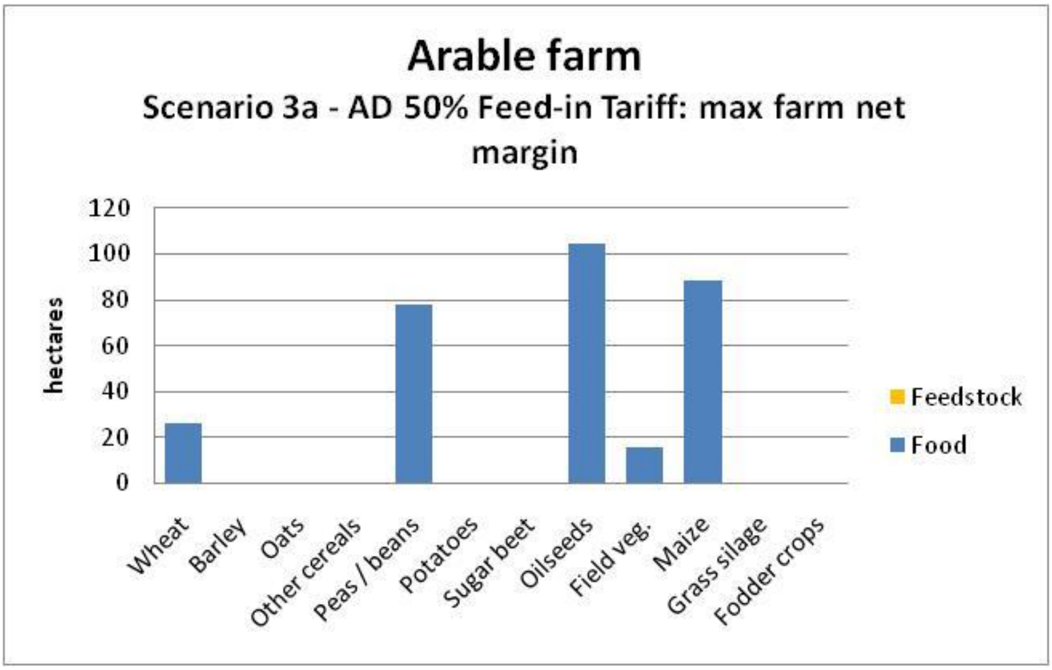
Table 17. Net margin of the specialist cereals farm under the reference run and scenario 2.

	Scenario 1 (£ p.a.)	Scenario 2 – prices +50% (% change)	Scenario 2 – prices +75% (% change)	Scenario 2 – prices +100% (% change)
Farm net margin	258,559	+10	+37	+71

5.4 Scenario 3 – abolition of feed-in tariff

In the third scenario, the conditions for agricultural commodity production as seen in the reference run are maintained, and the AD activity is also permitted, but the returns to the AD activity are varied. In this case two model runs are produced, first reducing the value of the feed-in tariff by half (from 11.5 pence/kWh to 5.75 pence/kWh) and in the second run the feed-in tariff is abolished altogether. Under these conditions the sole returns to the AD unit (assuming no use for the heat generated) would be the market value of the electricity sales. All other regulatory and environment parameters remain unchanged. Under this scenario the model is again tasked to maximize the farm net margin. *Summary: as per scenario 1, but with the feed-in tariff cut by half and then abolished.*

Figure 4. Arable farm. Scenario 3 (feed-in tariff) results



With the reduction in the value of the feed-in tariff by 50% (scenario 3a), the AD unit remains viable on the farm, but falls in scale from 495 kW (electricity output) to 85 kW. With receipts from electricity sales down to 8.75 pence per kW it is not economic to produce crops specifically for the digester and so the areas of whole-crop wheat and sugar beet grown under scenario 1 disappear (see Figure 4). Under this scenario AD feedstock is derived from residues from the food crops grown (no residues are available from maize because it is harvested whole-crop). The pattern of crop production returns exactly to that operating under the reference run, with the exception that the crop residues are put into the digester, rather than being left on the land.

When the feed-in tariff is withdrawn completely, resulting in returns to electricity sales of just 3 pence/kWh (scenario 3b), the AD activity is not viable and disappears completely, and farm operations return to the pattern seen under the reference run. Because, under scenario 3a there are no changes to the mix of crops produced in the reference run, there are also no changes in the volumes of nutrients purchased even though the AD unit is operating. This is because the feedstock for the digester is crop residues, which in the normal course of events would be left on the land, thus returning nutrients. With the AD unit operating, these same nutrients are returned to the land with the digestate. The same pattern of nutrient purchases is seen under scenario 3b.

Table 18. Whole-farm purchase of nutrients under scenario 3a.

	Reference run (kg)	Scenario 3a (single ROCS) (kg)	Scenario 3a (percent change) (%)
Nitrogen (N)	39,796	39,796	0
Potassium (k)	15,467	15,467	0
Phosphorous (P)	24,185	24,185	0

Under scenario 3a the use of on-farm labour is marginally higher (+6.5%) than in the reference run case due to the labour requirements of the AD unit. This is all farm labour, with no use of contractors in either case. Under Scenario 3b farm labour requirements are unchanged from reference run levels.

Farm net margin rises above the reference case to £92,652, (+11.6%) under scenario 3a, suggesting that AD can make a positive contribution to farm margin even at relatively small scales and even when limited to the use of crop residues as feedstocks.

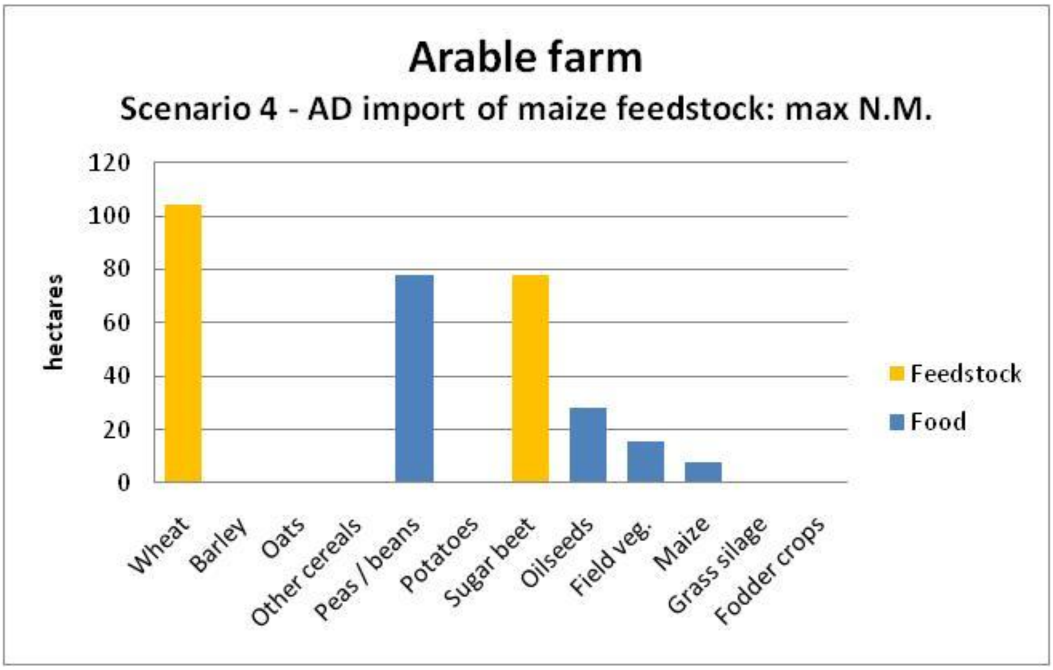
5.5 Scenario 4 - importation of feedstock onto the farm

In the fourth scenario, the conditions for agricultural commodity production prevailing in the reference run and scenario 1 are maintained, but the model is now permitted to import AD feedstocks onto the farm in the form of forage maize. Electricity prices include the current fixed export price and the full Feed-in Tariff. Under this scenario the model is again tasked to maximize the farm net margin. *Summary: as per scenario 1, but with imports of maize feedstocks onto the farm permitted*.

Under these scenario conditions the model operates the AD unit at the maximum capacity permissible, i.e. a scale equivalent to 500 kW of electricity output – a 1% increase on scenario 1. Under this scenario, the upper constraint on the size of the AD unit (constraining it to a maximum of 500 kW) is binding and this prevents the exploration of the maximum potential scale of AD unit that is possible on a farm of this size. To overcome this, the scenario is redefined to permit the deployment of an AD unit of any capacity. The limiting factor under this new arrangement, will obviously be disposal of the digestate, and in particular the constraint that the model cannot exceed the nutrient requirements of the crops being grown. *Summary: as per scenario 1, with imports of maize feedstocks onto the farm allowed and no upper limit on the size of the AD unit*.

Under this scenario digester capacity is 645 kW, adding an extra 150 kW (or 37%) to the capacity of digester seen under scenario 1.

Figure 5. Arable farm. Scenario 4 (importation of feedstock) results



Under this scenario the model produces a cropping pattern very similar to that seen under scenario 1, with 104 ha of whole-crop wheat and around 80 ha of sugar beet, both produced specifically for the digester, supplemented with residues from the oilseeds, peas and beans and field vegetables crops enterprises (see Figure 4). The increase in the scale of the digester is made possible by the importation of 4,223 t of forage maize. At an average yield of 45 t / ha, this would be the equivalent of renting an additional 94 ha of arable land.

Labour use is fairly similar to scenario 1, i.e. all available farm labour is employed, but there is a 76.5% increase in use of contractors under this scenario.

Table 19. Comparison of nutrient purchases between scenario 1 and scenario 4

	Scenario 1 (kg)	Scenario 4 (importation of feedstocks) (kg)	Percentage change
Nitrogen (N)	18,387	0	-100
Potassium (k)	9,768	0	-100
Phosphorous (P)	9,359	3104	-68.2

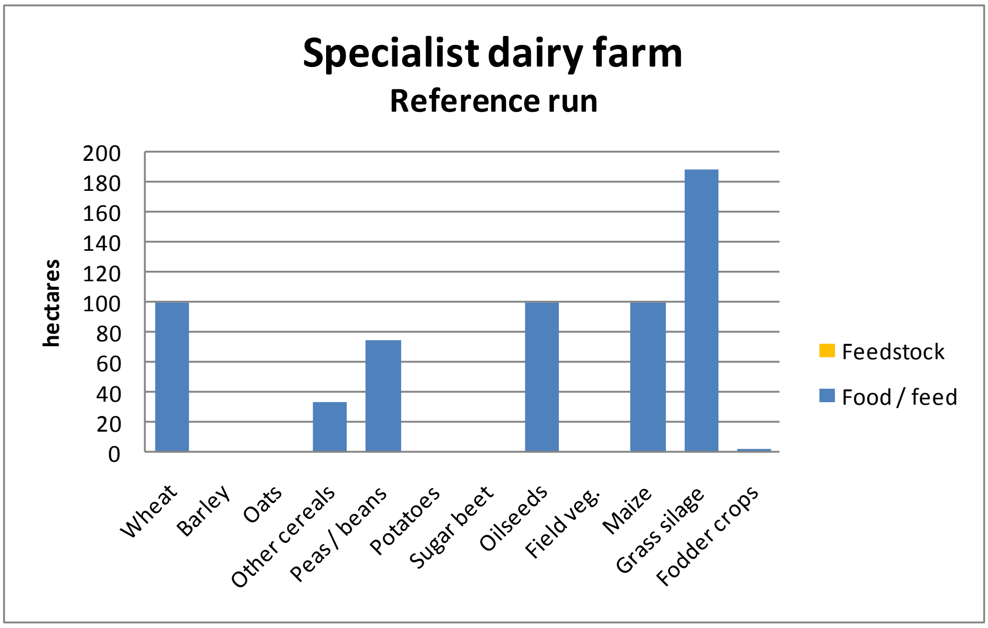
Under scenario 4, because of the importation of additional AD feedstock and therefore the availability of additional digestate, nutrient purchases are considerably lower than under scenario 1. Purchases of both N and K are eliminated completely and purchases of P falls 68%. The requirement for additional P purchases is due to the relatively low levels of P in the maize being imported onto the farm and the high growth requirements of the field-scale vegetable crops that are being exported off the farm. The fact that there are now no purchases of N and K reveals that disposal of digestate has become the limiting factor in the size of the AD unit. Under the scenario 4, the net margin of the model rises to £299,449, a 15.8% increase on scenario 1.

6. Model results – dairy farm

6.1 Reference run

In the absence of an AD activity the model produced 100 ha of maize and 233 ha of combinable crops (cereals and oilseeds) (see Figure 6). This compares very favourably with the mix of crops actually produced on the real-world farm on which this model is based where, in 2008, there was 200 ha of combinable crops and 150 ha of forage maize. In the case of the model run, both the combinable crops (excluding oilseeds) and the maize were produced specifically for dairy feeds, i.e. they were harvested whole-crop and ensiled. On the real-world farm in 2009 the remainder of the farm, 260 ha or so, produced grass, largely for silage. In the model 189 ha were used for grazing, also producing silage for the livestock activities. In the model result there were no imports of livestock feeds. The main difference between the model solution and the 2008 production on the real-world farm is the model's production on 75 ha of field beans, with this additional arable area being converted from leys.

Figure 6. Dairy farm - reference run results.



The nutrient application rates in the reference run are shown in Table 20. Here it can be seen that under the reference run there is no requirement to purchase inorganic potassium, as there are high concentrations of this available in the livestock slurry that is spread on the land.

Table 20. Whole-farm use of nutrients under the reference and scenario 1 runs.

	Reference run (kg)	Scenario 1(kg)	Percentage change
Nitrogen (N)	31,769	13,302	-58.1
Potassium (k)	0	0	N.A.
Phosphorous (P)	16,520	17,742	+7.4

Labour use under the reference run is 1,862 man days, plus another 1,778 man days of contractor time, i.e. 3640 man days in total.

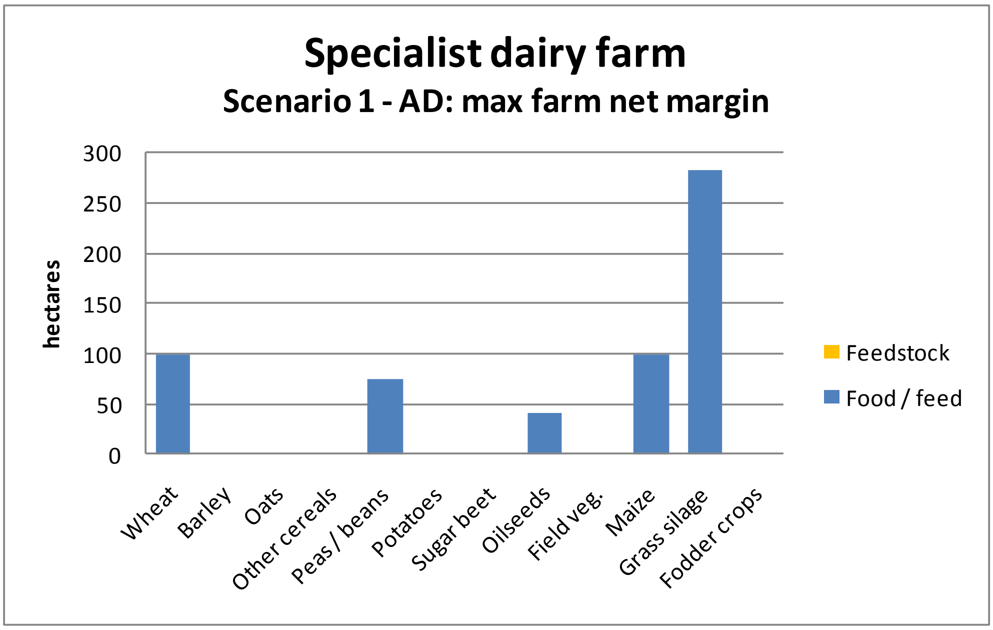
Under the reference run 550 dairy cows produce 4.7 million litres of milk and farm net margin is £609,827.

6.2 Scenario 1. AD: maximisation of farm net margin

Scenario summary: Market and policy conditions as they prevail in the reference run, plus the possibility of an AD activity (for more details see Section 5.2).

When AD is made available to the model, it is taken up at a digester scale equivalent to 195 kW. While there are some changes to the land use pattern on the farm (see Figure 7), these are not due to the introduction of crops to directly supply the digester, as the bulk of the feedstock comes from livestock slurry and no crops are grown specifically for the digester. The main land use changes are a decrease in the area of oilseeds produced, which falls from 100 ha to 42 ha, and the loss of 33 ha of other (minor) cereals production. The land so released is used to increase the area of the area of grass ley (by 93.6 ha) for silage production. This has had the effect of increasing P and K demand on the farm to allow for the disposal of greater volumes of digestate. Because the output of the field beans enterprise is being sold off the farm, i.e. not being ensiled for use as livestock feed, the crop residues are used in the AD unit to supplement the slurry feedstock.

Figure 7. Dairy farm. Scenario 1 (max farm net margin) results



Nutrient purchases for this scenario are shown in Table 20, which shows the major change to be savings in purchases of nitrogen, which falls 58% on reference run levels. This is largely due to the fact that the area of oilseeds has been reduced, being replaced by grass silage production, resulting in more complete nutrient recycling on the farm. The volume of purchased P increases by 7%. This increase is due to the replacement of oilseeds in the crop rotation with leys, which has more than double the oilseeds P requirements per ha. The positive financial impact of AD in terms of nutrient purchase savings on dairy farms will not be as great as on arable farms, because the main AD feedstock, cattle slurry, is already applied to land, thus there is a similar level of recycling of nutrients in both situations.

Under this scenario run the model continues to produce milk from 550 dairy cows, plus the farm also hosts 385 younger animals destined to be herd replacements. As in the case of the reference run, these livestock numbers are sustained without the requirement to import purchased feeds. This fact is important as it means that the risk of over-supply of cycled nutrients to land is reduced.

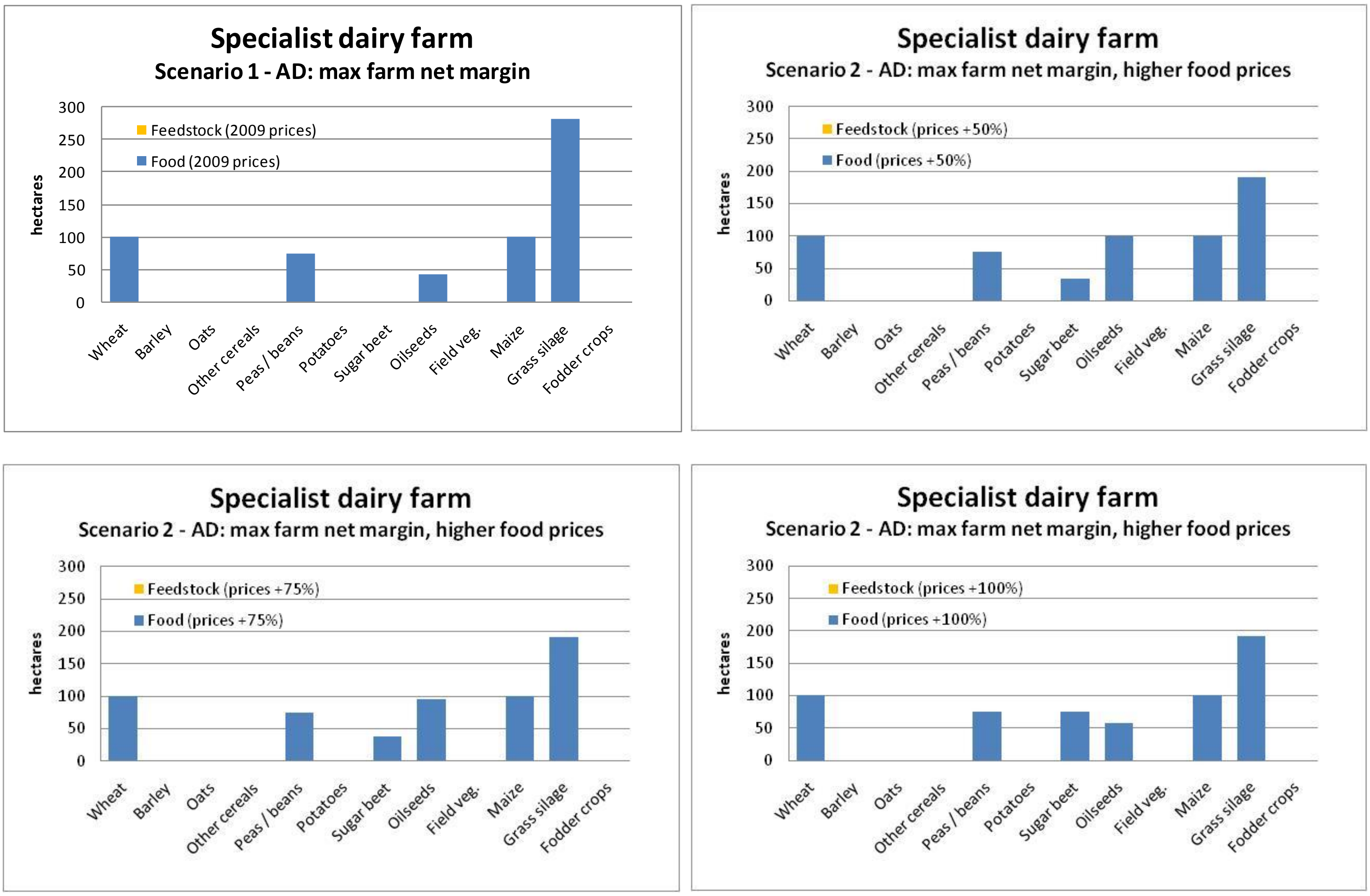
Because of the introduction of the AD activity, the farm under this scenario needs to purchase an additional 224 man days of contractor time (roughly one man year), while the farm margin increases to £646,882, a 6% increase on the reference run.

6.3 Scenario 2 – higher commodity prices

In Scenario 2, the conditions applying in Scenario 1 are carried over, but food and feed prices are increased in stepwise fashion until changes in the operation of AD on the farm are observed. Commodity price increases are applied uniformly across the board, with Step 1 introducing a 25% increase and step 2 a 50% increase and so on. The simplifying assumption is made that input prices remain unchanged (except purchased feeds), as does the export price for electricity. This scenario is designed to explore the competitive position of AD in relation to food and feeds production and in particular, identify the price thresholds at which AD becomes uncompetitive.
Summary: as per scenario 1, but with higher food and feed commodity prices.

Using the scenario 1 modelling outcome as a point of reference, a 25% increase in food and feeds prices generates only minor changes in the size of the AD operation, or the pattern of feedstock production. With price increases at 50% however, more significant changes are evident, as shown in Figure 8.

Figure 8. Dairy farm. Scenario 2 (higher commodity prices) results



The scenario involves a stepwise increase in prices until a doubling has been reached, and over this entire range the dairy enterprise is maintained at the original scale, i.e. 550 milking cows and 385 followers. Up to an increase in prices of 50% the areas of the main livestock feed crops, wheat, and maize are maintained unchanged, but the area of grass silage does fall, from 282 ha to around 190 ha. The land freed up is used to establish a small sugar beet activity and expand the area of oilseeds. Both crops are produced for food, rather than feed, in order to take advantage of the much improved margins that become available as a result of the higher prices. There are very few changes to this new pattern of production until prices double, at which point there is a transfer of some land from oilseeds to sugar beet production, but with all other crop areas remaining unchanged. As indicated, these changes are made possible by the transfer of 90 ha or so of grass ley to arable uses. This of course reduces the area devoted to the production of livestock feeds. However, there is no concomitant increase in the import of purchased feeds, as the model has compensated for a reduced grass ley area by switching from production of peas and beans for export off the farm, to their use on the farm for livestock feeds.

Under none of the commodity price increase scenario runs does the model produce any crops specifically for the AD unit. The AD unit maintains a presence in all runs at the following scales.

Table 21. Digester scale under a range of commodity price increases.

	Scenario 1	50% commodity price rise	75% commodity price rise	100% commodity price rise
kW	195.5	74.5	77.0	94.0

As can be seen, the 50% increase in commodity prices leads to a 62% decrease in the scale of the digester. This fall is a consequence of the loss of residues from the peas and beans crop in the digester. As indicated above, under all price increase scenarios peas and beans are produced for stock feed (ensiled whole-crop) rather than exported off the farm. Under the price increase scenarios therefore the digester uses only slurry as feedstock. The slight increases in the output of the digester over the price range is due to the increased availability of residues from the sugar beet crop as feedstock. The important point to note here however, is that at some scale, i.e. that which can be maintained largely by use of animal slurries, the AD unit is impervious to changes in the price of agricultural commodities.

Nutrient purchases under all of the price changes under this scenario are shown in Table 22. As the table shows, there is a large jump in the purchase of nitrogen under all of the Scenario 2 runs as a consequence of displacement of 90 ha or so of grass silage by sugar beet and oilseeds. This would seem counter-intuitive bearing in mind that the nitrogen requirement of grass ley (for multiple cuts of silage) is much higher than these other crops and so the loss of this crop should heavily reduce farm nitrogen demand. The explanation lies in the fact that the silage would have been used for livestock feeds and the nutrients put back to the land, while the oilseeds and sugar beet crops, and the nutrients they contain, are exported off the farm. Phosphorous levels are pretty constant over all scenario runs, while there are no potassium purchases under any conditions due to the high levels available in the slurry (levels that remain largely unchanged in the digester).

Table 22. Nutrient purchases under a range of commodity price increases.

		Scenario 2 price increase			Percent change from Scenario 1		
	Scenario 1 (kg)	50% (kg)	75% (kg)	100% (kg)	50%	75%	100%
Nitrogen (N)	13,302	28,974	28,187	24,143	117.8	111.9	81.5
Potassium (k)	0	0	0	0	0	0	0
Phosphorous (P)	17,742	15,787	15,760	16,128	-11.0	-11.2	-9.1

Under the scenario 2 runs, labour use on farm is fairly constant (see Table 23), ranging between 4 and 2 percent lower than the reference case. Some of this reduced labour requirement must be due to the reduction in the scale of the AD activity, with the scale of this fall diminishing as prices increase, because of the increase in the area of sugar beet, which has double the labour requirement of oilseeds and cereals.

Table 23. Labour requirements and farm net margin under a range of commodity price increases.

		Scenario 2 price increase			Percent change from Scenario 1		
	Scenario 1	50%	75%	100%	50%	75%	100%
Total labour requirement (man days)	3864.2	3710	3718	3776	-4.0	-3.8	-2.2
Farm net margin (£)	646,882	1,268,723	1,583,382	1,899,254	96.1	144.7	193.5

Farm net margin would obviously increase under this scenario due to the increased returns that higher prices bring. The scale of these increased revenues swamps any changes taking place in returns from the AD activity, which in any event are less than half of the level seen under scenario 1. The model suggests that a doubling of food prices would almost treble farm net margin. The scale of the net margin increases seen to result from these increases in revenues likely exaggerates the impact in the real world, as sustained prices rises of this kind would be accompanied by input cost increases, especially if the price increases were in part driven by increases in the cost of inputs.

6.4 Abolition of feed-in tariffs

Summary: as per scenario 1, but with the feed-in tariff cut by half and then abolished (for more details see Section 7.4).

With a 50% cut in feed-in tariff, the AD activity does not enter the model solution and the solution replicates the reference run exactly. A series of secondary runs have therefore been undertaken, varying the value of the feed-in tariff, to first identify the point at which AD again becomes economic in the context of a dairy farm, and second, report the scale of the AD activity deployed (see Table 24). These secondary runs reveal that AD becomes economic with a feed-in tariff placed somewhere between 40% and 50% lower than the present level, i.e. a total return of between 8.75 - 9.9 p/kWh. Because scenario 2 has shown that the AD activity on dairy farms is pretty much unaffected by commodity prices, the threshold that has been identified here would likely be relatively stable in the face of changing commodity market conditions.

Table 24. Scale of the dairy-farm based AD activity under a range of different cuts in feed-in tariff

	Scale of cut in feed-in tariff (%)					
	0	10	20	30	40	50
Scale of AD activity (kW)	195.5	108.5	97	74.5	59.5	0
Farm net margin (£/farm)	0	10,924	21,185	28,447	34,315	37,055

With decreasing AD scale a greater proportion of the establishment costs would be derived from own capital and this would make the smaller units economical at lower electricity returns, where a larger unit (requiring more borrowing) would not be. As the scale of the AD activity is seen to increase right up to the current level of feed-in tariff (see Table 24), this raises the question of whether scale would continue to increase at higher rates of feed-in tariff. The question is therefore asked, at what feed-in tariff would AD begin to displace the dairy activity, i.e. take land away from production of livestock feeds and/or reduce dairy cow numbers (again assuming that all feedstock must be sourced on farm)?

Table 25. Impact of increases in feed-in tariff on scale of dairy-farm based AD activity.

	Scale of increase in feed-in tariff (%)					
	0	10	20	30	40	50
Size of digester (kW)	195.5	335.5	395.5	395.5	395.5	433.5
Increase in farm net margin (£/farm)	0	25,728	59,528	97,679	135,829	175,600
Dairy cow numbers	550	550	535	535	535	503
Volume of imported feed (t)	0	0	0	0	0	0

As Table 25 shows, the scale of the AD activity increases with even a 10% increase in feed-in tariff (equivalent to an increase of just 0.6 pence per kW). AD scale remains constant from 20 and 40%, then another threshold is reached and increases in scale start again. The point at which AD begins to displace the dairy activity comes at the 20% increase in feed-in tariff, when dairy cow numbers decline by about 3%. It is interesting to note that the model does not attempt to maintain dairy numbers by importing cattle feeds to compensate for diversion of feed crops to the AD activity and this must be due to the fact that to do so would increase the supply of nutrients beyond what the land can carry. To enable it to increase the scale of the digester, the model has produced sugar beet specifically as a feedstock. A 50% increase in feed-in tariff (i.e. an increase of 2.9 p/kW) would result in a doubling of digester scale and a £175k increase in farm net margin. The model results suggest that had the Government set the feed-in tariff at 17.25 p/kWh (an increase of 50% on the current tariff), an additional 1,664,400 kWh of electricity output would be generated from just this single farm, at an additional cost to the exchequer of £95,703.

6.5 Scenario 4 - Importation of feedstock onto the farm

In the fourth scenario, the conditions for agricultural commodity production as seen in the reference run are maintained, and the AD activity is also permitted, but the model is now permitted to import AD feedstocks onto the farm in the form of forage maize and slurries from grazing livestock. Electricity prices include the current fixed export price and the full feed-in tariff. All other regulatory and environment aspects remain unchanged. Under this scenario the model is again tasked to maximize the farm net margin.

Summary: as per Scenario 1, but with imports of slurry and maize feedstocks onto the farm permitted.

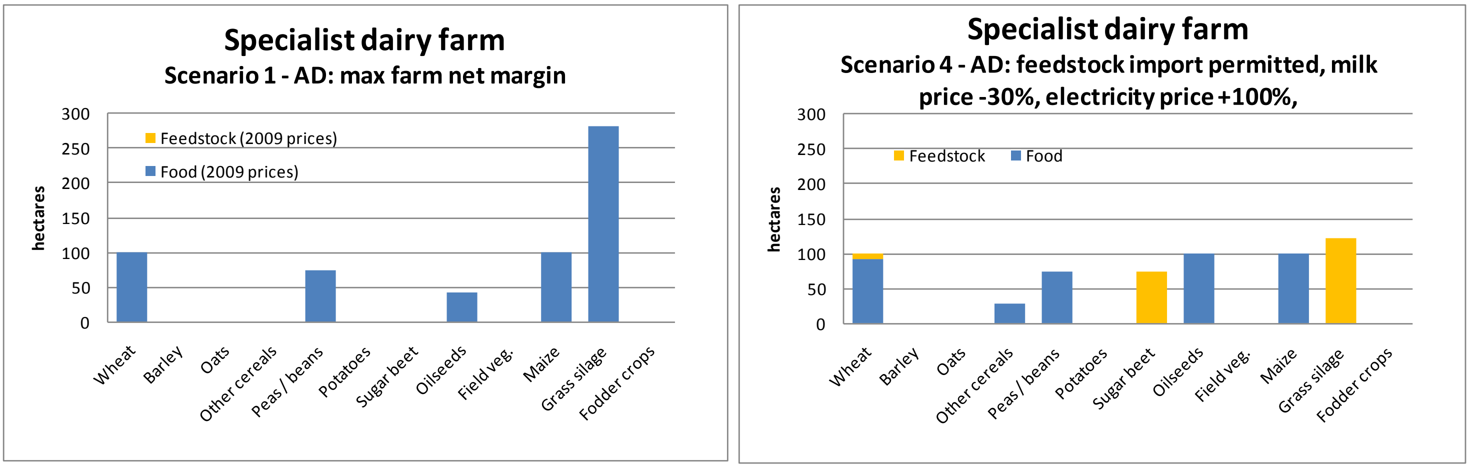
Under this scenario the model replicates exactly the pattern of crop production produced under scenario 1. However, given the opportunity to import additional AD feedstocks onto the farm in the form of raw slurry and maize silage, the model does so, importing 1,222t of maize silage. This has allowed the model to increase the scale of the AD activity to 245.5 kW. Under scenario 1, the model still had a requirement to import N and P, but was self sufficient in K. In order to avoid over-supply of K the model switches field beans production from stock-feed and exports the product off the farm, so exporting nutrients. This is sufficient to allow the import of nutrients in the form of forage maize. In compensation for the loss of livestock feed from field beans, the model increases output from grass leys by switching production to higher yielding land. What is apparent from this outcome, however, is that the farm is approaching self-sufficiency of N and P and is again self sufficient in K, giving it very little room for manoeuvre. This would imply that the possibility for import of further feedstock onto the farm would be very limited without scaling back the dairy enterprise and the export of more crops (and nutrients) off the farm. Based on the 2009 margins of the dairy and AD enterprises this would not be economically rational, as the dairy enterprise outperforms AD on a per ha basis. Should the relative margins of these two enterprises change however, perhaps due to a fall in the milk price, or an increase in the electricity price, the model might reduce dairy numbers and either divert feed crops to the digester, or export them off the farm and import feedstocks.

To explore this issue, i.e. to test how the model might overcome the problem of over-supply of nutrients in order to expand the scale of the AD operation, a revised scenario 4 has been run, in which import of feedstocks onto the farm is again permitted, but the milk price has been cut from 24 pence per litre, to 17 pence, a cut of around 30%. Under this scenario the impact of the milk price cut on business finances is very severe, with the farm net margin falling 49% from scenario 1. Consequently, the pressure to compensate by expanding the scale of the AD operation is strong.

In response, the model increases the scale of the AD operation to 337.5 kW and the size of the dairy herd is cut by 11% (a loss of 62 milking cows, plus associated replacements). This reduces the volume of nutrients available in slurry, but more importantly, allows the export off the farm of greater volumes of field beans, which are being produced on the most productive land.

If the relative terms of trade of the dairy and AD enterprises are skewed still further by, in addition to the 30% cut in milk price, a doubling of the electricity price, the size of the dairy herd is reduced by 51% (a loss of 330 milking cows) and the AD unit is increased in scale to 1mW. Under this scenario, some significant changes in cropping patterns are seen, as are shown in Figure 9, with 75ha of sugar beet being introduced specifically to supply the digester. Interestingly, the area of grass silage is reduced by roughly half, with the remaining area used to produce feedstock for the digester. The remaining dairy cattle are fed by forage maize and ensiled whole-crop wheat, plus aftermath grazing of grassland by herd replacements. Digester outputs are maximised by the import of 13,500t of silage maize, making the farm self-sufficient in N and K.

Figure 9. Dairy farm. Scenario 4 (importation of feedstock) results



The results thus far suggest that two factors determine whether a digester would be deployed on a farm of this size and type, and at what scale; these are, the financial performance of AD relative to the dairy enterprise, and the capacity of the farm to use, in compliance with good agricultural practice and NVZ constraints, the nutrients that would be made available in the digestate. It would seem that under the market conditions that prevailed in 2009, the establishment of an AD unit on a farm of this type, would add to the farm net margin, and that up to a certain scale, the AD activity would be complimentary to the dairy enterprise, i.e. it would use slurries as a feedstock and only surplus farm resources. However, beyond this scale, the AD unit has to compete with the dairy enterprise for farm resources and, based on the 2009 market, dairy prevails. Under conditions where AD outcompetes dairy in terms of net margin contribution per ha, the main factor limiting increases in enterprise scale would be the availability of land (i.e. the capacity of the land base to absorb the nutrients available in the digestate); other resources would not be constraining, i.e. more capital could be borrowed, more labour hired and AD feedstock bought in. However, there are some possible AD feedstocks that do not leave nutrient rich residues and it might be possible to import these as a way of increasing the scale of the digester without aggravating the problem of excess nutrient availability. One such feedstock is glycerol, a component of both animal and plant fats and oils and also a by-product (10%) of biodiesel production. This sweet, energy rich liquid generates large methane volumes (425m^3 per tonne) when used in digesters, but importantly, leaves no nutrient residues. Another benefit is that a pasteurisation unit is not required for the import of feedstock as it presents no biohazard (indeed, it is sometimes used in livestock feeds). There are, however, a few constraints to the use of this feedstock, primarily that: (i) domestic supplies are limited and it is sometimes necessary, even with current low levels of domestic AD uptake, to source from overseas; and (ii) there is a limit to how much glycerol can be added to the digester before bacterial performance is impaired; it is generally accepted that glycerol cannot amount to more than 10% of volatile solids. The price of crude glycerol is assumed to be £135/t (ICISpricing, 2010). As a means to further testing the potential uptake of AD on large dairy farms, the final scenario run in this series is based on scenario 1, and with importation of feedstocks permitted, with these to include glycerol. However, glycerol is only permitted to account for up to 10% of volatile solids in the digester.

Modelling shows that glycerol is taken up as a feedstock to the full extent possible, as long as the purchase price is low enough. Uptake of glycerol is therefore very price sensitive, as it has to compete against other imported feedstocks, such as forage maize, in terms of its contribution to farm net margin. When glycerol is available at £60 per tonne or less, it is competitive and, under this scenario 388t are purchased (this is the maximum permissible under this scenario and its use lifts digester output by 25%). However, at prices above this there is no take-up, and so glycerol would not seem economic at 2010 market prices.

7. Discussion and conclusions

7.1 Model validation

Validation of the arable and dairy models has occurred in two ways: (i) expert stakeholder evaluation of the structure of the models and the data used to populate them; and (ii) assessment of the reasonableness of the modelling outcomes. As a means to facilitating evaluation of the model structure and data, briefing documents were prepared describing the two models in detail, along with reference run and some scenario outputs. These briefing documents were sent out to a number of key stakeholders, including AD advisors and advocates, arable and dairy farmers, members of the Rural Business Research Consortium (who collect the Defra Farm Business Survey data), crop agronomists and fellow agricultural economists. Feedback from these stakeholders on the design of the models was generally very positive with only a few minor adjustments required in the light of comments, with these usually relating to rotational constraints and choice of data sources. Evaluation of the model outputs was carried out by members of the project team and a co-operating dairy and arable farmer. Both the arable and dairy farm models were judged to have performed well, i.e. they projected realistic reference run results. The reference run in this case is the ideal measure for evaluating model performance, because it is closest to real world conditions, i.e. there is no AD activity and the policy and market environment reflect the present (or rather the very recent past). The arable model produced a realistic rotational pattern of two thirds combinable crops and maize and one third break crops. Such a rotation would be sustainable both from a nutrient and disease management perspective. In the case of the dairy model, the validation exercise is strengthened by the fact that the model is based on a real-world farm, and so reference run outputs can be compared to real-world practices. This comparison showed that the reference run replicated very closely the livestock numbers and cropping pattern observed on the real world farm in 2008, i.e. the most recent year for which observational data are available, with 233 ha of combinable crops and maize projected, compared to 250 on the real farm in 2008. The main divergence was that 75 ha of grass ley was cultivated for field beans instead of grass silage.

Some differences between the model projections and the real world would be expected for a number of reasons. First, because the models, no matter how well designed, can never be more than simplified approximations of very complex farm businesses, which have far greater heterogeneity of resource quality than can be modelled (especially land quality) as well as the multiple management goals of the farmer (the model is designed to pursue only one goal – profit maximization). Second, farm planting decisions tend to be made over the whole cycle of a rotation (anything from 4 to 7 years), meaning that farmers are, to some extent, 'locked in' to pre-planned cropping patterns, even in the face of rapidly changing market conditions. The model on the other hand can react to the price and policy regime in the current year (farmers can only anticipate current year prices) and therefore the reference run outputs, strictly speaking, represent the direction in which the farm would go in subsequent years, in response to current year policy and market signals, assuming no other interventions. However, because we cannot anticipate how real-world farms will change, we can only compare reference run outputs to observations of the recent past. Because farmers cannot anticipate price spikes, and because they are constrained by their planned rotation, the management decisions tend to smooth out the kind of abrupt changes in cropping pattern that the models might make. However, these caveats aside, because the rotational constraints built into the model are demonstrably realistic, any solution that the model produces will be agronomically feasible, and economically optimal, and can therefore be viewed as a snapshot of one hypothetical year within the longer cycle of the farm rotation.

7.2 The economics of AD

AD is unlike other types of farm activity in that it is not constrained to use the same basic set of inputs to produce outputs. Where AD is concerned, a wide variety of feedstocks can be used as inputs to the fermentation process. In order to demonstrate that AD is economically viable therefore, it is necessary to show that (i) AD can compete economically with alternative uses of crops in order to secure a supply of feedstocks, and (ii) that AD is economically viable at the farm level. To this end, enterprise-based and farm-based net margin analyses must be carried out.

7.2.1 Comparative enterprise margins

The simplest form of analysis of the economics of AD is the estimation (using 2009 prices) of the net margins obtainable for AD by the use of particular feedstocks and the net margins obtainable by alternative uses of these same crops, i.e. selling them at prevailing market prices. Enterprise net margins for AD on a per hectare basis, based on a range of different feedstock types, and net margins for alternative uses of these same crops, are presented at Annex B. The AD net margins are net of all costs, including capital costs and represent returns to management and land. In the table at Annex B, three different AD net margins are provided, based on different assumptions concerning the rate of borrowing needed to fund AD capital expenditures. For the purposes of this assessment, it is assumed that capital borrowing is at a rate of 100%. To simplify the rather complex picture presented in Annex B, Table 26 below presents a selection of data to illustrate the relative economic performance of AD on a per ha basis, based on the use of seven different crop feedstocks, these being the best performers based on their AD net margin relative to alternative uses of the product.

Table 26. AD net margins per ha for the 7 best performing crop feedstocks in comparison with the net margins obtainable by alternative uses of these crops.

Top 7 best performing AD crop feedstocks	Net margin (£/ha) AD based on each feedstock	Net margin (£/ha) Conventionally marketed food/ feed	Percent increase in electricity returns for AD to outcompete alternative use of feedstock
Fodder beet	509	223	N.A.
Wheat (wholecrop)	275	53	N.A.
Sugar beet	195	56	N.A.
Forage maize	90	84	N.A.
Other cereals (rye, triticale)	-91	-66	3
Barley	-272	-124	13
Grass silage	-235	433	52

As Table 26 shows, based on 2009 electricity returns and commodity and input prices, AD outperforms alternative uses of four of the possible feedstock crops, i.e. fodder beet, wheat, sugar beet and forage maize. This list is quite limited, given the rather long list of crops that could be used as feedstocks for AD. For additional crops to be competitive as feedstocks, because the methane yield from these crops cannot easily be improved, the revenues from the use of the methane need to increase, i.e. by means of either higher electricity prices or a higher feed-in tariff. The final column in the table indicates the percentage increase in electricity returns that would be required to make the next three best performing AD feedstocks competitive with alternative uses. For ‘Other cereals’, i.e. minor cereals such as triticale and rye, this increase amounts to just 3% and this might easily be achieved within the scope of market price fluctuation for electricity sales (or based on electricity export prices agreed by contract). For barley, a 13% increase in returns from electricity exports would be required and for grass silage the required increase is 52%. For the feedstocks not listed in the table, due to high market returns for alternative uses, or due to low methane yields, even larger increases in electricity returns would be required to make AD a feasible use of the product.

Notable by its absence from Table 26 above is another type of feedstock - livestock slurry. In terms of its use as a feedstock. slurry is in a different category to crops, because use of slurry as a feedstock does not exclude other uses of this same product, i.e. for nutrient recycling. For this reason AD does not have to compete with other uses for the supply of slurry, because these uses are complementary. Other complementary feedstocks are available, in the form of residues from crops, where these have no economic uses except nutrient recycling (i.e. they are not sources of animal feed and cannot be sold in the market). The existence of complementary feedstocks means that AD can be economically viable at the farm level, even when it is not competitive enough to secure the supply of any feedstocks (especially crop feedstocks) that have alternative market-based uses.

However, on the basis of the analysis above, it would appear that AD provides better returns per farmed hectare for some of the major agricultural commodities than do alternative uses of these same crops. However, even this fact, and the existence of complementary feedstocks, is no guarantee that AD will be economically viable at the farm level. At the farm level, the introduction of AD may disrupt existing rotation patterns and production systems and the negative impacts of this may outweigh any marginal gains that accrue to the more profitable use of individual crops as AD feedstocks. It is also worth noting that any arable rotation supplying feedstocks for AD cannot use only crops for which AD is the most profitable end use. For example, in the table above, of the four best performing AD feedstocks, only fodder and sugar beet are break crops. In most arable rotations a variety of break crops are required to best manage soil nutrients and reduce disease pressure, so alternatives to beet crops would be needed and AD enterprise margins would likely be lower in these cases than for alternative uses. Of course, this does not exclude the possibility of farms producing both AD feedstock and food/feed crops from the same rotation.

7.2.2 Viability of AD at the farm level

Broad judgements about the economic viability of AD at the farm level are difficult to make because the viability of AD is dependent on the context in which it operates and this context is very heterogeneous. The context includes the farm type, or farming system, which will determine the availability of different types of feedstock, farm size, and the scale at which AD is operated. The modelling approach adopted in this study has made this complexity more manageable, buy focussing on the two most AD-prospective farm systems (arable and dairy) and setting the farm size to reflect common commercial scales of operation for these farm types in England. Additionally, the LP modelling approach allows the model itself to select an appropriate (or optimal) scale of AD operation, together with choice of feedstocks, within a set of crop rotations appropriate for each farm. The modelling exercise demonstrates that on typical commercial arable and dairy farms in England, and at 2009 prices, AD is comfortably commercially viable (see Table 27).

Table 27. Net margin changes resulting from the introduction of AD to typical arable and dairy farms in England (2009 prices)

	Arable farm			Dairy farm		
Scenario	Scale of AD unit operated (kW)	Change in farm net margin resulting from adoption of AD (£)	AD contribution to net margin (£/kW)	Scale of AD unit operated (kW)	Change in farm net margin resulting from adoption of AD (£)	AD contribution to net margin per kW (£/kW)
2009 Reference	495	175,564	355	195	37,055	190

In the case of the 'average' arable farm, AD is taken up at a scale of almost one half megawatt, adding £175 k to the farm net margin. In the case of the dairy farm, even though the farm is twice the size of the arable farm in area terms, the AD unit adopted is less than half that seen on the arable farm. The difference in AD scale is due to the fact that in the case of the dairy farm, the AD unit is using a greater proportion of complementary feedstocks, in this case livestock slurry. Livestock slurry has much lower methane content per unit volume than crops and crop residues and digester output is accordingly reduced. Because, in the case of the dairy farm, the digester scale is relatively small, capital and operating costs per kW are proportionately higher and so net margin contribution per kW of electricity output is also rather lower than for the larger unit on the arable farm.

The two farm type models demonstrate two different ways in which AD can be operated on farms. In the case of the arable farm AD is a competing enterprise, displacing existing economic activities by appropriating their outputs to serve as inputs to AD. In the dairy case AD is a complementary activity, sitting alongside existing economic activities with minimal displacement (at least, this is the case where digester scale is less than 200 kW). In this case, the model is able to find sufficient feedstocks to operate the AD unit at a profit, without having to reduce the size of the dairy unit.

In summary then, medium to large-scale AD is economically viable on medium and large arable farms in England. At 2009 prices, it would be economically rational to make AD the main commercial activity on the farm, with cropping activities geared to servicing the digester.

AD is economically viable, at small to medium scales, on medium and large scale dairy farms in England. The model results show that, at 2009 prices, it would be economically rational to retain the dairy focus of the business and introduce AD alongside this, at a scale that can be supported by complementary feedstocks, including slurries and surplus crop production.

7.2.3 The cost of borrowing

Perhaps the most significant issue raised by stakeholders commenting on the modelling exercise concerned the assumptions made about capital borrowing. In the modelling exercise it was assumed that the capital needed to construct the digester was wholly borrowed, at a 4% interest rate, with full capital repayment over 10 years. Various stakeholders have implied that, at the present time, farmers would struggle to borrow, at least for investment in AD, on such favourable terms. Anecdotal evidence suggests that because farm-based AD is relatively undeveloped in the UK, banks and other lenders are unfamiliar with the technology and lack confidence in the business model. This uncertainty multiplies perceived risk and this elevated risk is reflected in higher interest charges and demands for other forms of security, such as requirements to secure the loan against farm assets, or the deposit of a capital sum to cover future interest payments. While it might be expected that, or at least hoped that AD will eventually become more commonplace and lenders more familiar with the business model, leading to cheaper capital finance, it is accepted that at the present time, borrowing may not be as cheap as has been assumed in this modelling exercise. In view of this, it would be remiss not to explore the implications of higher costs of borrowing on the economics of AD. Table 28 examines the impact of higher interest charges on AD net margin (per hectare) for the six best performing AD feedstocks. The table replicates part of Annex

Table B3, but estimates separate per hectare enterprise net margins for interest rates of 4, 6 and 8%.

Table 28. AD net margin calculations for the six best performing feedstock crops based on a range of interest rates charges on borrowed capital

	Wheat	Barley	Other cereals	Sugar beet	Maize	Fodder beet
Outputs						
Yield (whole crop t/ha)	38.6	37	31.3	82	45.4	91
Methane yield (m3/t)	125	82	110	81	99	74
Methane output (m3/ha)	4825	3034	3443	6642	4495	6734
Electricity output (kWh/ha)	14475	9102	10329	19926	13485	20202
Electricity price (plus feed-in tariff) (£/kWh)	0.145	0.145	0.145	0.145	0.145	0.145
Total output value (£/ha)	**2099**	**1320**	**1498**	**2889**	**1955**	**2929**
Variable costs (crops)						
Fertilizer (£/ha)	12	11	10	15	11	13
Sprays (£/ha)	149	107	65	175	39	144
Seed (£/ha)	47	53	48	160	148	130
Other variable costs (£/ha)	0	0	0	0	0	0
Casual labour	0	0	0	0	0	0
Gross margin (£/ha)	**1891**	**1149**	**1375**	**2251**	**1759**	**2642**
Fixed costs						
Crop labour (£/ha)	59.5	59.5	59.5	156.4	148.9	223.4
Crop fixed costs (£/ha)	243.35	243.35	243.35	389.79	243.35	389.79
AD labour (£/ha)	73.8	46.4	52.7	101.6	68.8	103
AD maintenance cost (£/ha)	159.2	100.1	113.6	219.2	148.3	222.2
AD Other fixed costs	289.9	182.0	206.6	398.5	269.7	404.0
Total fixed costs (excl. AD interest) (£/ha)	**1615.8**	**1421.4**	**1465.8**	**2055.5**	**1669.1**	**2132.4**
AD Interest (£/ha) @ 4% p.a.	790	790	790	790	790	790
Net margin (£/ha) (4% i/r)	**275.2**	**-272.4**	**-90.8**	**483.5**	**89.9**	**509.6**
AD Interest (£/ha) @ 6% p.a.	880	880	880	880	880	880
Net margin (£/ha) (6% i/r)	**185.2**	**-362.4**	**-180.8**	**393.5**	**-0.1**	**419.6**
AD Interest (£/ha) @ 8% p.a.	955	955	955	955	955	955
Net margin (£/ha) (8% i/r)	**110.2**	**-437.4**	**-255.8**	**318.5**	**-75.1**	**344.6**

Note: capital is assumed to be 100% borrowed.
Note: AD interest includes both interest and capital repayment, averaged over the 10 year repayment period.
Note: AD 'Interest' is allocated uniformly to each hectare utilised for agriculture on the farm (312ha for the arable farm).

As can be seen from the table, AD net margins are adversely affected by higher borrowing charges and with an interest rate of 8% some enterprises that formerly showed a positive net margin for AD, no longer do so. The obvious case here is maize. Bearing in mind the current industry assumption (perhaps even the word 'fixation' would be appropriate) that maize is the most suitable crop feedstock, it is easy to see why farmers considering adopting AD would lose interest with borrowing costs at this level. However, what is also apparent from these calculations is that, even with these high borrowing costs, AD yields a positive net margin when using feedstocks such as whole-crop wheat and beet (more on the choice of feedstocks in Section 7.4 following).

7.3 AD and nutrient cycling

Digestate residues are excellent sources of nutrients (mainly N, P, K). In fact, the nutrient profile of the digestate coming out of the digester is much the same as the nutrient profile of the feedstocks that are fed in. The modelling has shown that if all crops grown on the farm are used as AD feedstocks, then the recycling of these nutrients through the timely application of the digestate to land largely eliminates the need for inorganic nutrient purchases. Under these circumstances only modest nutrient purchases would be required (whether inorganic or otherwise) in order to replace nutrients lost from the soil during the cultivation and growing period, for example through leaching into ground water.

Table 29. Savings in nutrient purchases, in volume and cost terms, resulting from arable and dairy farms operating AD units

	Arable farm			Dairy farm		
Nutrient	Nutrient purchases without AD (Reference run) (Kg)	Change in nutrient purchases with AD (%)	Savings in cost of nutrients (£, 2009 prices)	Nutrient purchases without AD (Reference run) (Kg)	Change in nutrient purchases with AD (%)	Savings in cost of nutrients (£, 2009 prices)
N	39,796	-53.8	11,133	31,769	-58.1	9,603
P	15467	-39.5	3,848	16,520	+7.4	(770)
K	24,185	-59.6	12,687	0	0	0
Total cost saving			27,668			8,833

As Table 29 shows, total cost savings on nutrient purchases are far greater for arable farms than for dairy, for several reasons. First, the AD unit is operating at a larger scale on arable farms and therefore more digestate is available. Another reason is that on the arable farm without AD, the great majority of the crop biomass produced is exported off the farm, so exporting nutrients, which have to be replaced from other sources. When AD is operating, a larger proportion of crops are retained on the farm and the nutrients they contain returned to the land. On the dairy farm, the bulk of the feedstock for the digester is derived from cattle slurry and the nutrient contained in this would have been returned to the land even without the AD unit. The savings in N purchases seen in Table 29 are due to the model greatly reducing the oilseeds area (this crop was largely being sold off the farm) and increasing the area of grass leys, thus allowing more complete nutrient recycling.

From the data in Table 29 it can be seen that around 16% of the improvement in farm net margin resulting from adoption of AD on the arable farm is due to savings in the cost of purchased inputs. The purchased nutrient savings on the dairy farm amount to 24% of the net margin increase, but this figure needs to be interpreted in the light of the loss of the oilseed area, as this change in management, while facilitated by the arrival of AD, is not entirely dependent on it.

7.4 The choice of AD feedstocks

A large array of agricultural crops, crop residues and wastes are potentially available for use as feedstocks in farm-based AD operations in the UK. In terms of choice of feedstocks, the thinking among those associated with farm-based AD in this country continues to be narrowly focussed on livestock slurries on livestock farms, and forage maize on arable farms. The choice of these two is predicated on the availability of slurries, and on the large biomass yields obtainable from maize, together with the relatively common occurrence of this crop (and the infrastructure for harvesting and storing it in large quantities) in UK agriculture for use as a livestock feed. Forage maize is also widely used as an AD feedstock crop in some EU countries. The analysis presented here confirms the use of animal slurries on livestock farms as an obvious and economically rational choice. However, the endorsement of forage maize as the crop of choice for feedstock is more muted. The choice of feedstock crop is determined by a number of factors, only one of which is the amount of biomass per ha that can be derived. Assuming that it is agronomically possible to produce a worthwhile yield of a crop, the other factors to be considered are: methane yield per tonne of crop; the net margin obtainable on that crop through use as an AD feedstock, i.e. it should break-even as a minimum; and the net margin obtainable on that crop from alternative uses. While maize is one of the crops where use as an AD feedstock provides a better net margin return than alternative uses, it does not provide the largest margin over alternative uses. This fact is reflected in the relatively low levels of planting of this crop as an AD feedstock on both the dairy and arable farm models. More commonly, wheat and sugar beet are grown for use as feedstocks, these being harvested whole-crop and ensiled for storage in the same way that forage maize would be. This finding suggests that the continental model of arable AD, based on maize feedstocks, is not directly transferrable, and that a UK AD model needs to be developed, based on the use of beet and whole-crop wheat as feedstocks.

The modelling has shown that on typical commercial dairy and arable farms there is no pressing requirement to import feedstocks onto the farm for AD to become economically viable. AD units of significant size can be supported solely through feedstocks derived from the farm and these can lead to significant improvements in farm financial performance.

While the above is true, the modelling has also shown that the financial contribution that the AD unit makes to the farm net margin can be significantly increased by increasing the scale of the AD operation beyond the level which can be sustained by farm-sourced feedstocks alone. The range of feedstocks that can potentially be imported includes all temperate crops, plus exotics, as well as industry, catering and household food wastes. However, the availability of imported feedstocks is not a panacea for AD as the cost of production or acquisition of many feedstocks would make their use uneconomic. Additionally, multi-megawatt AD units would still not be feasible on many farms, even assuming that the capital required to build them is available, because there is a constraint on the capacity of the land to absorb the digestate residue from the AD unit, or rather, the nutrients contained therein.

If farms, even after the spreading of digestate, have an additional need to import nutrients, perhaps because they are continuing to export some commodities off the farm, then there is scope to import feedstocks onto the farm. This can be done to the point when the requirement to import one or more nutrients ceases. At this point a threshold is reached, where the nutrients supplied to the land through AD digestate meets the requirements of the growing crops and any additional applications would breach either good agricultural practice advice, or worse, agronomic practice regulations. In these cases, further increase in the scale of the digester can only be achieved if digestate can be exported off the farm, or more land rented in. Of course, constraints can be relaxed to some extent by the choice of the feedstocks that are imported. It does not make sense, for example, to import cattle slurries onto farms that already have a domestic slurry supply. Cattle slurries are very rich in potassium (K) and if all crops and grasses grown are fed to the livestock, the digestate from the AD unit will supply pretty close the growing requirements of the next year's crops even without feedstock imports. This situation will be even more likely if concentrate livestock feeds are being imported, as these will contain nutrients also. However, even when requirements for K are being met from domestic slurries, there may still be a requirement to import N and P, so import of feedstocks with low K might be feasible. The ideal feedstock import under conditions of nutrient constraint is something like glycerin, which has very high methane yields, but adds no nutrients to digestate residues.

There is much talk in the UK AD sector about the real value in AD operations coming from gate fee receipts, i.e. fees charged to third parties for the acceptance of digestable organic wastes. This modelling exercise has shown that gate fees are not necessary for AD to be economically viable on UK farms. This study did not attempt to model either the import of food wastes or the impact of gate fees, but what can be surmised from the modelling work is that, while gate fees would contribute to AD revenues, this option would only be feasible, due to constraints on the disposal of the digestate, if the imported feedstocks displaced home-grown feedstocks in the digester. This would be rational for example if imported feedstocks could be obtained more cheaply than home-grown feedstocks could be produced, or if higher costs were offset by higher methane yields.

7.5 The impact of AD on cropping pattern and livestock numbers

On the arable farm, with the introduction of AD, the model does not turn the whole farm over to the production of feedstock crops, but some changes are introduced to rotations to allow the supply of feedstocks. In this case an area of beet crops is introduced and the area of cereals expands, at the expense of both maize and oilseeds. In this case, beet largely replaces oilseeds as a break crop. Generalising from these results to the arable sector as a whole, it is apparent that the impact of AD on arable rotations would be fairly minor, because the crops that are most economically viable for use as feedstocks are already widely grown. While a radical reshaping of rotations is unlikely, a few issues are worth highlighting. The first is that while wheat would likely retain its dominant position in the rotations of farms with AD, the role of oilseeds as a break crop may diminish and the prevalence of beet crops may increase. It is also apparent that the concern sometimes voiced in the industry about a large expansion in the area of forage maize would be unlikely, once UK farmers realise the potential of other crops as feedstocks, particularly whole-crop wheat and beet crops.

On the dairy farm the headline observation is that, on the basis of 2009 market conditions, AD as an activity is complementary to dairying and therefore co-exists with the dairy activity rather than replacing it; cattle numbers are therefore maintained. The changes in cropping pattern on the farm are also fairly minor, involving some loss of combinable crops and an increase in grass leys. These changes are driven largely by the need to meet the difficult challenge of managing nutrient cycling. Grass leys have higher nutrient requirements than most other crops, particularly P and K, and so an expanded grass area increases the capacity of the farm to absorb digestate.

7.6 AD and farm employment

In this modelling exercise it has been assumed that the labour requirement for a 500 kW AD unit is 250 man days, or 1.14 man years (assuming 220 days worked p.a.). This equates to a labour requirement of 4 hours per kW. It is also assumed that the labour requirement per kW decreases with increases in digester scale, i.e. smaller digesters have higher labour requirements per kW. In estimating the consequences for labour use resulting from adoption of AD in the modelling exercise, account has to be taken of both the labour changes attributable directly to the AD unit, and any other labour changes that might occur as a consequence of adjustments to other farm operations; Table 30 shows these calculations.

Table 30. Changes in farm labour requirements for arable and dairy farms as a consequence of AD adoption

	Arable	Dairy
Digester labour requirement (man days)	+30.9	+17.0
Other labour adjustments on the farm (man days)	-7	+7.4
Net labour change per farm (man days)	+23.9	+24.4

The direct labour requirement for the AD unit on the arable farm is a little under 31 man days, while the whole-farm labour requirement only increases by 24 man days. This means that saving of 7 man days have been made elsewhere on the farm. Labour savings are likely due to the introduction of the wheat crop for AD feedstock, which has low labour requirements, i.e. in comparison with crops like maize. Because there are relatively few crops where, in terms of net margin contribution, AD out-competes alternative uses, there will be a tendency on farms taking up large-scale AD units to simplify, to some extent, farm rotations, based around this limited set of crops. This will have the effect of simplifying the farm systems and will result in some labour savings.

On the dairy farm, the introduction of AD adds 17 man days to the farm labour requirement, but taken over the whole farm labour use increases by 24.4 man days, meaning that an additional 7.4 man days have been added elsewhere. This is largely because of the switch away from oilseeds to grass silage production. As was the case with the arable farm, something of a simplification of cropping pattern takes place, with a greater emphasis on grass based silage production, although this enterprise is more labour intensive than cereals.

In 2008 there were 12,300 dairy holdings in England and Wales and 34,300 arable holdings (Cereals and General Cropping)[15]. If just 10% of arable and dairy farms adopted digesters on the scale modelled here, this would result in 81,977 additional man days of labour (or 372 FTEs) on arable farms, and 30,012 additional man days (or 136 FTEs) on dairy farms. Total direct additional labour requirement on farms in England and Wales would be 508 FTEs.

7.7 The viability of AD in a changing policy and market environment

While the modelling exercise has demonstrated that AD is economically viable on commercial arable and dairy farms in England and Wales in the current (or rather 2009) market and policy conditions, the question remains, how robust would the economic model be in the face of changes to this operating environment? This is a question that is posed by many in the farming industry and the lack of data on this issue must act as a significant barrier to uptake of this technology on farms. This study explored this question by adjusting, in a number of different modelling scenarios, both the policies that support AD on farms and the market prices of agricultural commodities.

7.7.1 The impact of changing commodity prices

AD has to compete for feedstock supplies against alternative uses for them, i.e. food and feed sales (or on-farm use of livestock feed). At 2009 prices, AD out-competes these alternative uses, on a net margin basis, in the case of a number of crops, notably beet crops, wheat and maize. Table 31 shows the threshold for commodity price increases at which AD can no longer economically compete for individual crop feedstocks.

[15] Defra (2010c)

Table 31. Price increases required before AD can no longer secure crops as feedstocks.

	Net margin advantage for AD compared to the best alternative use (£/ha)		
Price change	Wheat	Fodder beet	Maize
Zero (i.e. 2009 price)	222	286	6
+25%	46.3	-104	-192.6
+50%	-129.5		

According to this analysis it would be uneconomical to divert any crops to AD uses if commodity price rises were much above 25% across the board. As recent events have shown, price rises of this magnitude are quite feasible, even in the short term, and this would suggest that AD would be vulnerable to relatively modest rises in prices. The farm level modelling, however, shows that AD is more robust than these calculations suggest. On the arable farm AD is still deployed when across the board commodity price rises reach 75% (above 2009 levels). However, in this case, the provision of feedstocks from energy crops has all but ceased, and the digester is supplied from crop residues, i.e. a complementary source. This observation demonstrates that AD use of complementary feedstock sources is unaffected by commodity price rises, because there is no alternative market use for these products. The availability of these complementary feedstocks bestows a degree of economic resilience on AD, in the face of market price fluctuations, that is most evident on the dairy farm. The modelling shows that with a 50% increase in commodity prices, the scale of the AD unit operated on the dairy farm falls by half, but that higher rates of price increase have no further deleterious effect on the AD operation. The reason for this resilience is that once the AD unit has shrunk to the point that it can be sustained entirely using livestock slurries (complementary feedstocks), it is impervious to further commodity price changes.

Before concluding the discussion of this issue, some other points need to be aired. While the enterprise net margin analysis shows that price rises of more than 25% would divert all crop feedstocks to alternative uses, it is seldom the case that markets experience such uniform price rises. In reality, price rises, even those driven by upward general pressure on costs of production, will affect some commodities more than others and it is therefore quite likely that, except in exceptional market conditions, one or more crops would be available cheaply enough to make its use as an AD feedstock economically viable. It should also be remembered that many farmers will go on producing enterprises for some years when more profitable alternatives are available and even when they are loss making. This has been commonly seen in the dairy sector in recent years. Farmers are accustomed to market price fluctuations and so do not base production decisions on prices in any one year, but rather on an expectation that enterprises will be profitable when averaged over a number of years, even if they are loss making in one or more years in that period. The same principle will apply to planning decisions involving AD.

In these analyses, the simplifying assumption has been made that when prices for commodities rises, prices of AD outputs, including electricity, do not. However, it is often the case that an element of commodity price increases results from rises in energy and fuel costs. It is reasonable to expect therefore, that should commodity prices experience sustained, long-term increases, a significant part of these increases would be due to general rises in the costs of production and this would include energy and fuel costs. In the face of commodity price rises therefore, some compensating increase in the value of AD outputs should be expected.

7.7.2 Impact of changing renewable energy policies

AD is currently supported in the UK by Government renewable energy policy. Of most importance for this analysis are the existence of feed-in tariffs and the availability of agreements to guarantee the export price of electricity. In this modelling exercise, a fixed export price of 3 pence/kWh has been assumed, plus a feed-in tariff amounting to 11.5 pence/kWh. Total returns to electricity sales are therefore assumed to be 14.5 pence/kWh. While these policy arrangements are intended to be for the long term (as much as 20 years in the case of the feed-in tariff), farmers experience with the changing Common Agricultural Policy, including the phasing out of dairy quotas, have made them wary of assuming continuity of policy. This is also an obstacle to widespread AD adoption. For this reason, this study sought to explore the impacts of changes to government energy policy on the economic viability of AD. In terms of changes to policy, the worst-case-scenario has to be the reduction, or the abolition, of the feed-in tariff.

On the arable farm, the AD unit survives a 50% reduction in the value of the feed-in tariff, but the scale of the unit falls sharply from 495 kW to just 85 kW. At this scale the AD unit is supplied only from complementary feedstocks, i.e. crop residues. When the feed-in tariff is withdrawn, AD disappears completely. A 50% cut in feed-in tariff would eliminate AD from the dairy farm, but further exploration of this threshold has shown that AD would still be viable with a cut in feed-in tariff a little greater than 40%.

Once AD is operating solely on complementary feedstocks, there is no longer an issue of AD having to compete for feedstocks with alternative uses, and so the issue then is solely the return on the capital invested. With the feed-in tariff reduced by 50%, even though complementary feedstocks are available on the dairy farm, the returns to capital investment are less than the replacement cost of the AD plant and the enterprise is deemed by the model to be unviable.

7.8 The importation of feedstocks onto the farm

Other work packages in this study have dealt with some of the non-economic issues associated with the importation of AD feedstocks onto farms, e.g. the regulatory environment and the additional technologies that would have to be deployed. This work package is concerned primarily with the impacts of feedstocks import on the economics of the AD operation, farm production decisions and nutrient management.

A number of factors will influence the scale of AD plant that can operate on any single farm; these are: availability of capital, disposal of digestate and availability of feedstocks. Of the three, perhaps the most immediately constraining will be the availability of feedstocks, particularly if feesdstocks cannot be imported. To explore this issue additional scenario runs were undertaken permitting the importation of selected AD feedstocks.

When imported feedstocks are made available, digester scale is increased on the arable farm to 645kW from 496, an increase of 30%, supporting this extra capacity with 4,223t of imported forage maize (note that other types of crop feedstock were not available to the model). It is important to note that the model could have supported additional growth in the capacity of the digester by transferring more land on the farm to the production of digester feedstocks, but chose to maintain the production of some crops for export off the farm because their enterprise net margins outperform AD. It should also be noted that only forage maize was available to the model to import, so in the real world other feedstocks might have been preferable. This result merely serves to illustrate that it is economic to import AD feedstocks on arable farms to increase digester output and that in some cases it might be more economical to do so than produce feedstocks on the farm. With unlimited availability of imported feedstocks, what generally constrains AD scale is capacity to dispose of the digestate. What the scenario modelling demonstrates is that once the farm is self sufficient in one or more nutrients it can import no further volumes of these nutrients.

When given the opportunity to import nutrients the dairy farm also imports them, in this case forage maize (in preference to livestock slurries) as a means to increasing AD scale and therefore farm net margin. As with the arable farm, enterprises that outcompete AD (i.e. the dairy herd) are retained on the farm and importation of feedstocks ceases when the capacity of the land to absorb the digestate is reached. When a nutrient-free feedstock (glycerol) becomes available, the model imports this and the scale of the digester is increased again.

The conclusion from this is that AD is profitable, on the basis of the use of a number of feedstocks, whether these are produced on the farm, or imported. Farms may choose not turn all of their land over to feedstocks production for a number of reasons, including that alternative uses make a bigger contribution to farm net margin than would production of AD feedstocks, or because the production of crops uneconomic as feedstocks is necessary to maintain healthy rotations. In these circumstances farms will turn to feedstock imports where prices are low enough. Ultimately, even with the availability of low nutrient feedstocks, what limits AD scale is the availability of land to take the digestate.

References

Andersons (2008) A Detailed Economic Assessment of Anaerobic Digestion Technology and its Suitability to UK Farming and Waste Systems. The Andersons Centre, Melton Mowbray.

Anon (2006) Handreichung - Biogasgewinnung und nutzung. Gülzow, Germany, Fachagentur Nachwachsende Rohstoffe e. V.

Bockman. O. O., Kaarstad, O., Lie, O. H. and Richards, I. (1990) Agriculture and Fertilizers. Norsk Hydro, Oslo.

British Biogen (2003) Anaerobic Digestion of farm and food processing residues: Good Practice Guidelines.

Defra (2010a) Earnings and hours of agricultural and horticultural workers: England and Wales – 12 months ending September 2009. January 2010. http://www.defra.gov.uk/evidence/statistics/foodfarm/farmmanage/earningshours/documents/earnings-hours.pdf

Defra (2010b) Farm Gate Prices: Commodity Prices. http://defra.gov.uk/evidence/statistics/foodfarm/farmgate/commodity/index.htm (accessed on 17/05/10).

Defra (2010c) Agriculture in the United Kingdom 2009 (updated 16 February 2010). http://www.defra.gov.uk/evidence/statistics/foodfarm/general/auk/latest/excel/index.htm

Edwards, S. G. (2004) Influence of agricultural practices on fusarium infection of cereals and subsequent contamination of grain by trichothecene mycotoxins, *Toxicology Letters*, 153(1), pp 29-35.

Farmers Weekly (2009) The Farmers Weekly Group, Reed Business Information Ltd, Sutton, Surrey. 28 August 2009.

Farmers Weekly Interactive (2010) http://www.fwi.co.uk/Articles/2008/01/04/108901/British-Sugar-agrees-increased-sugar-beet-price-for-2008-and.htm

Fried, M. and Broeshart, H. (1975) *Plant and Soil*, 43, pp 707-711.

FNR (2009) Handreichung Biogasgewindnung und Nutzung. Fachagentur Nachwachsende Rohstoffe e.V. Gülzow, Germany.

Greenfinch (2009) Personal Communication.

ICISpricing (2010).
http://www.icispricing.com/il_shared/Samples/SubPage99.asp (accessed on 28 July 2010).

Köttner, M., Kusch, S., Kaiser, A. and Dörrie, D. (2008) Economic Modelling of Anaerobic Digestion / Biogas Installations in a Range of Rural Scenarios in Cornwall. A report to the Cornwall Agri-food Council by the International Biogas and Bioenergy Centre of Competence and the Renewable Energy Association. August 2008.

KTBL (2002) Betriebsplanung Landwirtschaft 2002/2003. Kuratorium für technik und Bauwesen in der Landwirtschaft e.V., Darmstadt, Germany.

Lang, T. (2008) Farming in the Eastern Counties of England. University of Cambridge, Department of Land Economy.

Maff (2000) Fertiliser Recommendations for Agricultural and Horticultural Crops (RB209), London, The Stationary Office. See Appendix 5. Also available online at:
http://www.defra.gov.uk/foodfarm/landmanage/land-soil/nutrient/fert/rb209/documents/intro.pdf

Nix (2008) Farm Management Pocketbook, 38th Edition. Wye College, University of London.

Nix (2010) Farm Management Pocketbook, 40th Edition. Wye College, University of London.

NNFCC (2009) NNFCC 08-006 A Detailed Economic Assessment of Anaerobic Digestion Technology and its Suitability to UK Farming and Waste Systems: AD cost model (Andersons).
http://www.nnfcc.co.uk/metadot/index.pl?id=7197;isa=DBRow;op=show;dbview_id=2457

RBR (2010) Rural Business Research, Farm Business Survey data for England: Cereals farm fixed costs for agricultural activities.
http://www.farmbusinesssurvey.co.uk/regional/home.asp

SAC (1992) Technical Note: Fertiliser Series No 14. Fertiliser allowances for manures and slurries. Edinburgh, SAC.

SAC (2008) The Farm Management Handbook 2008/09. The Scottish Agricultural College, 2008.

SAC (2009) The Farm Management Handbook 2009/10. The Scottish Agricultural College, 2009.

Salter, A. (2009) personal communication.

Soffe, R. J. (Ed.) (1995) The Agricultural Notebook, 19th Edition. Blackwell Science, Oxford.

UKFCWP (2004) Report of the UK Farm Classification Working Party, 2004. http://www.defra.gov.uk/evidence/economics/foodfarm/reports/documents/ukfcwp.pdf

Yeatman, O. and Jefferies, E. (2009) *Farmers Weekly*, 6 November 2009, pp 26-27.

Annex A . Input prices and other reference data.

Table A.1. Prices of a range of agricultural inputs (2009 prices)

Input	Price (£/kg, hour)
Fertilizers (straights)	
N	0.52
P	0.63
K	0.88
Sprays	Varies by crop
Slurry	8
Seed	Varies by crop
Other variable costs	
Regular hired labour (£/hour)	9.31
Contractors (£/hour)	18.62
Interest rate	4%

Note: labour costs consist:

	£/hour	
Basic salary	8.19	(Defra, 2010a)
NI	1.04	(Nix, 2008)
ELI	0.08	(Nix, 2008)

Note: Contractor costs vary widely depending on type of operation and the use of machinery. The simplifying assumption has been made that contractor costs are double the cost (to the farm business) of regular hired labour.

Note: Slurry price is based on its nutrient content (N, P K) multiplied by the value (purchase price) of individual nutrients:

Table A.2. Nutrient value of grazing livestock slurry and estimate of sale value.

	Nutrient content (kg/t)	Nutrient price (£/t)	Value of nutrients in slurry (£/t)
N	3.5	0.52	1.8
P	1.1	0.63	0.7
K	5.8	0.88	5.1
		Total slurry price (£/t)	7.6

Annex B . Enterprise margins

Table B.1. Food and feed crop margins (2009 commodity and input prices)

	Wheat	Barley	Oats	Other cereals	OSR	Peas	Beans	Sugar beet	Potatoes	Maize	Fodder beet	Field veg.	Grass silage
Outputs													
Yield (t/ha)	8.3	6.4	6.5	6.0	3.4	4.4	3.8	58.6	45.0	45.4	60.0	75.0	38.0
Price (£/t)	84.7	74	73.4	80	219.5	116.8	116.8	24	125.6	17.5	26	95	30
Total output (£/ha)	**703.01**	**473.6**	**477.1**	**480**	**746.3**	**513.9**	**443.8**	**1406**	**5652**	**794.5**	**1560**	**7125**	**1140**
Variable costs													
Fertilizer (£/ha)	151	135	100	130	147	38	40	181	313	131	164	135	252
Sprays (£/ha)	149	107	75	65	126	130	109	175	537	39	144	144	16
Seed (£/ha)	47	53	51	48	38	97	58	160	690	148	130	156	16
Other variable costs (£/ha)	0	0	0	0	0	0	0	288	419	0	0	1200[4]	
Casual labour (£/ha)	0	0	0	0	0	0	0	0	750	0	0	342	0
Gross Margin (£/ha)	**356**	**178.6**	**251.1**	**237**	**435.3**	**248.9**	**236.8**	**602**	**2943**	**476.5**	**1122**	**5148**	**856**
Fixed costs													
Labour (£/ha)	59.5	59.5	59.5	59.5	52.1	52.1	52.1	156.4	506.5	148.9	223.4	819.3	178.7
Other fixed costs	243.35	243.35	243.35	243.35	194.90	146.45	146.45	389.79	1070.28	243.35	389.79	1168.28	243.35
Net margin (£/ha)	53.2	-124.3	-51.8	-65.9	188.3	50.4	38.3	55.8	1366.2	84.3	508.8	3160.4	433.9

Note: For commodity prices see Annex E.
Note: 'Other fixed costs' (£/ha) are estimated on the basis of total farm fixed costs (excluding labour) divided by total farmed area, then weighted for each enterprise on the basis of enterprise labour use per ha.
Note: Silage data based on 2 cuts per year from intensively managed leys.
Note: Field vegetables 'Other variable costs' are notional costs for expenditures such as packaging, grading, storage and marketing.

Table B.1 (continued)

	Dairy
Outputs	
Annual average Yield (litres)	8500
Average milk price (p/l)	24
Calf value (£ annual share)	85
Cull cow (£ annual share)	135
Total output (£/cow/year)	**2260**
Costs	
AI (£/cow)	56
Vet and medicines (£/cow)	80
Other livestock costs (£/cow)	75
Concentrates (@£200/t) (£/cow)	527
Cost of rearing heifer replacement (annual share, £/cow)	444
Forage variable costs	
Silage (@£335/ha) (£/cow)	67
Gross Margin (£/cow	**1011**
Labour (£/cow)	179
Fixed costs (£/cow)	706
Net margin (£/cow/year)	126

Source: adapted from SAC (2009)

Note: Calf value: assumed that a calf is retained as a replacement one year in 3. Assumed first calving at 2 years and for another 2 years. Calves not retained as replacements are assumed sold at 3 weeks at £128 (2009 prices) and therefore annual share is £128 * 2 / 3 = £85.
Note: Herd culling rate assumed to be 25%, therefore cull value of dairy cow will be realised one year in 4. Annual share of cull value is 25% of 2009 cull cow sale value of £541.
Note: Concentrates assumed fed at rate of 0.31kg/litre of milk produced; silage assumed fed at rate of 1.06kg/litre (silage yield is 45t/ha).
Note: Labour costs: 2.4 man days (24 hours) @ £9.31/hour.
Note: Net margin per forage ha assumes a notional stocking rate of 2 dairy cows per ha.
Note: Farm gate milk price data supplied by DairyCo (annual average of 19 dairies), as reported in: Farmers Weekly, 7 August 2009.
Note: Average milk yield taken from Nix (2010).

Note: Fixed cost breakdown:

Cost	**£/head**
Machinery fuels and oils	67
Machinery repairs and other	85
Machinery depreciation	122
General farming costs, of which:	
Bank charges and professional fees	43
Water, electricity and general costs	122
Share of net interest payments	79
Land and property costs, of which:	
Rent paid	126
Maintenance, repairs and insurance	3
Depreciation of buildings and works	44
Miscellaneous fixed costs	15
Total fixed costs	706

Source: RBR 2010. Fixed costs based on livestock share of whole farm fixed costs for specialist dairy farm, and attributed to productive dairy animals on a per head basis. Fixed costs thus allocated to productive dairy animals may be an over-estimate as this includes a share that might be allocated to other types of livestock on the farm, e.g. dairy followers.

Table B.2. Digester feedstock margins (using whole crop yields) (2009 input and 2009 electricity prices)

	Wheat	Barley	Oats	Other cereals	OSR	Peas	Beans	Sugar beet	Potatoes	Maize	Fodder beet	Field veg.	Grass silage
Outputs													
Yield (whole crop t/ha)	38.6	37	37	31.3	46.2	40.1	50.7	82	45	45.4	91	95	45
Methane yield (m3/t)	125	82	76	110	50	47	47	81	27	99	74	74	70
Methane output (m3/ha)	4825	3034	2812	3443	2310	1885	2383	6642	1215	4495	6734	7030	3150
Electricity output (kWh/ha)	14475	9102	8436	10329	6930	5655	7149	19926	3645	13485	20202	21090	9450
Electricity price (plus feed-in tariff) (£/kWh)	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145
Total output value (£/ha)	**2099**	**1320**	**1223**	**1498**	**1005**	**820**	**1037**	**2889**	**529**	**1955**	**2929**	**3058**	**1370**
Variable costs (crops)													
Fertilizer (£/ha)	12	11	8	10	12	0	0	15	25	11	13	11	20
Sprays (£/ha)	149	107	75	65	126	130	109	175	537	39	144	144	16
Seed (£/ha)	47	53	51	48	38	97	58	160	690	148	130	156	16
Other variable costs (£/ha)	0	0	0	0	0	0	0	0	419	0	0	0	
Casual labour	0	0	0	0	0	0	0	0	750	0	0	342	0
Gross Margin (£/ha)	**1891**	**1149**	**997**	**1375**	**829**	**593**	**870**	**2251**	**-1892**	**1759**	**2642**	**2405**	**1318**
Fixed costs													
Crop labour (£/ha)	59.5	59.5	59.5	59.5	52.1	52.1	52.1	156.4	506.5	148.9	223.4	819.3	178.7
Crop fixed costs (£/ha)	243.35	243.35	243.35	243.35	194.90	146.45	146.45	389.79	1070.28	243.35	389.79	1168.28	243.35
AD labour (£/ha)	73.8	46.4	43	52.7	35.3	28.8	36.5	101.6	18.6	68.8	103	107.6	48.2
AD maintenance cost (£/ha)	159.2	100.1	92.8	113.6	76.2	62.2	78.6	219.2	40.1	148.3	222.2	232	103.9
AD Other fixed costs	289.9	182.0	168.7	206.6	138.6	113.1	143	398.5	72.9	269.7	404.0	421.8	189
AD Interest (£/ha)	790	790	790	790	790	790	790	790	790	790	790	790	790
Total fixed costs (£/ha)	**1615.8**	**1421.4**	**1397.4**	**1465.8**	**1148.5**	**1192.7**	**1246.7**	**2055.5**	**2498.4**	**1669.1**	**2132.4**	**3539**	**1553.2**
Net margin (£/ha) (100% capital borrowed)	**275.2**	**-272.4**	**-400.4**	**-90.8**	**-319.5**	**-599.7**	**-376.7**	**483.5**	**-4390.4**	**89.9**	**509.6**	**-1134.0**	**-235.2**
Net margin (£/ha) (90% capital borrowed)	**354.2**	**-193.4**	**-321.4**	**-11.8**	**-240.5**	**-520.7**	**-297.7**	**562.4**	**-4311.4**	**168.9**	**588.6**	**-1055.0**	**-156.2**
Net margin (£/ha) (80% capital borrowed)	**433.2**	**-114.4**	**-242.4**	**67.2**	**-161.5**	**-441.7**	**-218.7**	**641.5**	**-4232.4**	**247.9**	**667.6**	**-976.0**	**-77.2**

Note: electricity generation assumes 35% generator efficiency.

Note: Interest is charged on capital borrowed for the establishment of the AD unit.

Note: Fertilizer costs are low due to digestate from the AD unit being returned to land. Purchased fertilizer requirement for land receiving digestate equates with 15% N losses due to leaching (see Section 3.11).

Note: The sugar beet enterprise does not incur 'other variable costs' when used as AD feedstocks as these costs are primarily for haulage.
Note: AD labour costs estimated as £0.0051/kWh, based on a 500 kW unit, generating 3,507,550 kWh of electricity, incurring £18k of labour costs p.a. (see Table 10 above).
Note: AD 'Maintenance cost' is £0.011/kWh, based on a 500 kW unit, generating 3,507,550kWh, incurring £37,500 of maintenance costs (see Table 10 above).
Note: AD 'Fixed costs' include: electricity, insurance and other costs, amounting to £69,000 for a 500 kW unit, or £0.02/kWh.
Note: AD 'Interest' (on capital investment in the AD unit and silage clamp) is £246,600 pa for a 500 kW unit (includes both interest and capital repayment), equating to £0.07/kWh, and is allocated uniformly to each hectare utilised for agriculture on the farm (312 ha for the arable farm).

Note: Other crop fixed costs consist, on a per ha basis (averaged over the whole farm):

Cost	**£/ha**
Machinery fuels and oils	52
Machinery repairs and other	45
Machinery depreciation	89
General farming costs, of which:	
Bank charges and professional fees	19
Water, electricity and general costs	51
Share of net interest payments	19
Land and property costs, of which:	
Rent paid	54
Maintenance, repairs and insurance	2
Depreciation of buildings and works	10
Miscellaneous fixed costs	41
Total fixed costs	382

Source: RBR (2010).

Annex C. Nutrient content of crops (whole crop): comparison of data sources.

Table C.1 . Comparison of nitrogen content estimates from Table 12 with equivalent estimates provided by Maff (2000) and KTBL (2002).

Crop enterprise	Nitrogen (N) (kg/t whole crop)		
	Table 12	MAFF (2000) RB209	KTBL (2002)
Winter wheat	3.3		3.5
Winter barley	3.1		3.5
Winter oats	2.1		3.5
Other cereals (triticale)	3.7		7
Oilseed rape	2.9		3.5
Field peas	3.7		3.5
Field beans	2.9	No data available	3.5
Sugar beet	1.0		1.8
Potatoes (maincrop)	4.1		3.2
Maize (forage)	1.8		3.8
Other fodder crops (fodder beet)	1.2		1.8
Field-scale veg (swedes)	0.7		3.2
Grass silage	3.1		3.8

Table C.2. Comparison of potassium content estimates from Table 12 with equivalent estimates provided by Maff (2000) and KTBL (2002).

Crop enterprise	Potassium (K) (kg/t whole crop)		
	Table 12	Maff (2000) RB209	KTBL (2002)
Winter wheat	1.3	2.5 [1]	4.5
Winter barley	1.4	2.4 [1]	4.5
Winter oats	1.2	3.0 [1]	4.5
Other cereals (triticale)	1.7	2.0 [1]	6.1
Oilseed rape	0.7	1.3 [1]	4.5
Field peas	0.9	3.2 [2]	4.5
Field beans	0.7	3.2 [2]	4.5
Sugar beet	0.8	7.5	2.5
Potatoes (maincrop)	4.7	5.8	5.8
Maize (forage)	2.3	4.4	4.5
Other fodder crops (fodder beet)	1.4	5.0 [3]	5.0
Field-scale veg (swedes)	1.1	2.4 [4]	2.4
Grass silage	2.5	6.0 [5]	4.5

Table C.3. Comparison of phosphate content estimates from Table 12 with equivalent estimates provided by Maff (2000) and KTBL (2002).

Crop enterprise	Phosphate (P) (kg/t whole crop)		
	Table 12	Maff (2000) RB209	KTBL (2002)
Winter wheat	1.3	1.8 [1]	1.1
Winter barley	1.4	1.5 [1]	1.1
Winter oats	1.2	1.5 [1]	1.1
Other cereals (triticale)	1.7	1.7 [1]	3.4
Oilseed rape	0.6	1.1 [1]	1.1
Field peas	0.8	1.7 [2]	1.1
Field beans	0.7	1.7 [2]	1.1
Sugar beet	0.5	1.9	1.0
Potatoes (maincrop)	2.8	1.0	1.0
Maize (forage)	0.8	1.4	1.6
Other fodder crops (fodder beet)	0.6	1.2 [3]	0.9
Field-scale veg (swedes)	1.1	0.7 [4]	0.7
Grass silage	1.5	1.7 [5]	1.6

Notes:

1. Maff (2000) denominate the estimate of whole crop nutrients over the grain. To derive the estimates in the table above, the grain denominated estimates are multiplied by notional grain yields to give per ha estimates, then divided by whole-crop yields.
2. Vining pea estimate used.
3. Kale estimate used.
4. Swedes – roots only.
5. Grass silage (25% dry matter).

Annex D. Labour requirements for all agricultural farm operations included in the model

Crop / livestock category	Labour coefficient (man days of labour per LSU, or per ha, per year)
Wheat	0.8
Barley	0.8
Oats	0.8
Other cereals (triticale)	0.8
Oilseeds	0.7
Sugar beet	2.1
Field peas and beans	0.7
Main crop potatoes	6.8
Field scale vegetables (swedes)	11
Maize	2
Fodder crops (fodder beet)	3
Grass silage	2.4
Dairy	4.3
Beef	1.2
Sheep	3.1
Leys	0.5
Permanent pasture	0.5
Rough grass	0.2

Note: 1 man day assumed to be 8 hours.
Note: Standard Labour Requirements (SLR) derived from Nix (2010), where premium values are provided for farms with 200ha or more of arable land. Premium data used in this case.
Note: SLR values for dairy cows varies by milk yield, in this case the values for a yield of 8,000l/cow/year have been used.
Note: SLR for beef based on 0.9 man days per lowland single suckling cow, rebased to LSU.
Note: SLR for sheep based on 0.33 man days per lowland ewe p.a., rebased to LSU.

Annex E. Commodity prices used in the model, 2009, various sources.

Crop / livestock category	2009 prices (£ / t, kg or litre)	Source
Wheat (feed)	84.7	Defra (2010b)
Barley (feed)	74.0	Defra (2010b)
Oats	73.4	Defra (2010b)
Other cereals (triticale)	80	See Notes to table
Oilseeds	219.5	Farmers Weekly (2009)
Sugar beet	24	Farmers Weekly Interactive (2010)
Field peas and beans	116.8	Defra (2010b)
Main crop potatoes (GB farm gate average)	125.6	Defra (2010b)
Field scale vegetables (swedes)	95	SAC (2009)
Maize	17.5	Nix (2010, p87)
Fodder crops (fodder beet)	26	SAC (2009)
Grass silage	30	Nix (2010)
Hay (big bale)	49	Defra (2010b)
Dairy (milk pence/litre)	22.5	Defra (2010b)
Dairy (cull cow, pence/kg/lw)	86.7	Defra (2010b)
Beef (all finished steers, p/kg/lw)	149.8	Defra (2010b)
Sheep (finished lambs,p/kg/lw)	136	Defra (2010b)

Note: Defra and Farmers Weekly prices are taken for the end of August 2009 (Defra, 2010b; Farmers Weekly, 2009).
Note: Price of triticale assumed to be £4 lower than that for feed wheat, following advice from Nix (2010, p20).
Note: For peas and beans, data for beans are used.