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Exploring Farm Anaerobic Digester Economic Viability in a Time of Policy Change in the UK

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Abstract: The combination of a post-Brexit agricultural policy, the Global Methane Pledge announced during the last United Nations Climate Change Conference in Glasgow (COP26), and urgency of meeting climate goals means the UK has a unique opportunity to create an exemplar through recognition of the benefits of small-scale farm anaerobic digesters that valorise on-site wastes for renewable electricity and heat, cushioning agri-businesses against energy perturbations. To explore economic viability of farm-based biogas production, combinations of support levels, energy prices, capital cost, internal rate of return (IRR), and digestate value were analysed, employing a 550-cow dairy farm with access to other agricultural wastes. A 145 kWe system utilising 100% of CHP electricity (grid value: £0.1361 per kWh) and 70% of the heat (heating oil value: £0.055 per kWh) could achieve an IRR above 15.5% with a median electricity tariff of £0.1104 per kWh at a heat tariff from £0.0309 to £0.0873 per kWh thermal. Under a subsidy-free regime, the same system could achieve a 10% IRR with electricity prices in the range £0.149 to £0.261 per kWh. High fertiliser prices could increase digestate value, further improving viability. With late-2021 high energy prices, the technology approaches subsidy-free viability, but uptake is unlikely unless wider environmental and societal benefits of on-farm systems can be explicitly valued.

Keywords: agricultural wastes; biogas production; anaerobic digestion costs; economic viability; UK policy; Brexit; feed-in tariff; renewable heat incentive



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1. Introduction

In the last decade, financial incentives based on energy production have created significant growth in anaerobic digestion (AD) installations in the United Kingdom (UK), with the number of agricultural plants increasing from 25 in 2010 to 344 in 2020 [1]. AD can capture uncontrolled greenhouse gas (GHG) emissions from the biodegradation of organic wastes and from farm management activities [2,3], making a useful contribution to overall GHG reductions (potentially by 6% for the UK, according to the Anaerobic Digestion and Bioresources Association [4]), thus helping the UK to meet its Paris Agreement and COP26 Global Methane Pledge commitments. Farm AD, particularly using on-site/local wastes for biogas generation and recovery of digestate, has myriad benefits beyond renewable energy generation alone: it can reduce GHG emissions [3,5–7], improve soil organic matter [8], facilitate improved nutrient management [9–11] thereby reducing the need for artificial fertiliser [12,13], kill pathogens and weed seeds if appropriately applied [14–16], provide opportunities for skilled rural employment [17,18], and create additional revenues in rural areas [19].

Clearly, a breakthrough in deployment of anaerobic digestion does not only depend on technical aspects and is strongly moderated by incentives provided [20]. Growth in the UK's on-farm AD industry started with the introduction of the Pollution Control Grants in the late 1980s, then stagnated when these were withdrawn in the mid-1990s [21,22]. The

digesters were relatively small in size, usually under 350 m³, and the biogas was primarily used in boilers for heating [21,23]. During the eight years prior to the introduction of the 2010 Feed-In Tariff (FIT), only seven projects [24] running on farm feedstocks had been commissioned under the 2002 Renewables Obligation system, which was designed for production of renewable electricity.

The AD FIT incentivised electricity production from biogas via combined heat and power (CHP) units. It was followed by the introduction in 2011 of the Renewable Heat Incentive (RHI), which was designed to encourage heat use and biomethane production. Since CHP has relatively low electrical efficiencies of approximately 30% for smaller units and up to 45% for larger ones, the RHI introduced the possibility of improved AD economics if most of the CHP heat produced could be beneficially utilised at a relatively low cost. The policy, however, primarily encouraged the introduction of biomethane-to-grid plants, with 108 biomethane plants operational when it closed in March 2021, compared to seven heat-only plants [1].

Incentives that recognise only the energy contributions of AD have encouraged the construction of larger plants with a greater proportion of crop inputs. Agricultural CHP plants over 250 kWe comprise 68% of the UK total at an average of 1 MWe_{eq}, with agricultural biomethane plants averaging 789 m³ biomethane per hour or approximately 3.1 MWe_{eq} [1]. Concern over using land to provide feedstock for crop-only digesters led to the requirement for sustainability criteria to encourage the use of 'waste' AD feedstocks and to limit the amount of crop material fed to digesters [25], which can result in indirect land use change when land for biofuel crops displaces that used for food or feed. The sustainability criteria have been built into the Green Gas Support Scheme (GGSS), which was introduced in 2021, funded by a gas consumer levy and specifically designed for AD biomethane grid injection. The policy aims to support larger biomethane plants, with the highest out of three tariffs being paid to installations injecting up to 60,000 MWh year⁻¹ of biomethane into the gas grid (approximately 750 m³ biomethane per hour).

Most farmers are unwilling or unable to find sufficient feedstocks or to raise the significant investment required for such a large plant [26], due to factors such as uncertainty about the future, where best to target new investments and concerns over the underlying profitability of their farm businesses. Thus, there remains an AD policy gap for UK farmers who wish to valorise their on-site feedstocks by installing smaller, less capital-intensive AD systems. Additionally, because on-farm organic wastes such as slurries and manures contain less energy than an equivalent tonnage of crop biomass, the challenge is to introduce a mechanism that can make such systems a sufficiently attractive economic proposition for farm businesses to invest in.

In their life cycle assessments on AD systems, Mesa-Dominguez et al. [27] and Styles et al. [28] noted that the greenhouse gas balances of AD plants improved by maximising waste and minimising crop inputs, utilising any CHP heat produced and covering digestate stores. Mesa-Dominguez et al. [27] concluded that energy-based incentives do not create the most sustainable deployment of AD. To illustrate this context, it is worth highlighting that a cubic metre of digester space costs the same whether it is fed on 1 m³ of cow slurry at 23 m³ biogas tonne⁻¹ of fresh feedstock or 1 m³ of maize at 220 m³ biogas tonne⁻¹ of fresh feedstock, but the waste slurry produces only one-tenth of the energy of the crop. The slurry digester, however, has better overall environmental credentials, mitigating 1449 kg CO_{2eq} tonne⁻¹ of dry matter [27], because it utilises material that would otherwise create greenhouse gas emissions through its production, storage, and handling. Mesa-Dominguez et al. [27] concluded that public FIT/RHI funding should integrate consequential life cycle assessment (CLCA) and eco-systems services criteria into sustainability criteria for the most effective climate protection. In line with this, a CLCA conducted by Beausang et al. [29] for co-digestion of grass silage and cattle slurry found lower proportions of grass silage to be more sustainable, thus highlighting the environmental benefits of slurry-based farm AD plants.

Sustainability criteria were designed into the UK's non-domestic RHI and GGSS from the outset, and subsequently added to the accreditation process for the FIT from April 2017. With the 2020 Brexit withdrawal of the UK from the European Union (EU), spelling the end of EU agricultural support mechanisms in the UK, an opportunity arises to include anaerobic digestion in post-Brexit environmental schemes on UK livestock farms, particularly dairy farms, where it can make significant positive impacts [30]. The policy dilemma, therefore, is to address how on-farm AD, which utilises local or on-site wastes can be encouraged in a cost-effective way, particularly to mitigate the GHG emissions associated with livestock farming, thus valuing the technology for its wider ecosystem services deliverables (such as nutrient recycling, pollution mitigation, GHG reduction), rather than simply the production of energy [31]. While this is particularly acute in the UK due to current changes in regulation and support, similar challenges exist in many countries trying to encourage the implementation of AD by using financial support mechanisms that directly influence the digester size [32,33].

A unique opportunity to advance on-farm AD in the UK is currently given for policymakers. This opportunity is characterised by the following: a prevailing policy gap for small farm-scale AD to valorise on-site materials such as slurries and manures; the need to introduce a completely new agricultural policy that values the environment; increased impetus to meet climate targets; and high current fossil energy prices, which also means elevated prices for artificial fertilisers. Such prices favour the on-site production of renewable electricity and heat, including through AD.

In the light of COP26 aspirations, the introduction of new post-Brexit agricultural support mechanisms and a current UK policy vacuum for small farm AD that utilises on-site/local waste feedstocks, the aim of this study is to determine what level of policy support might be required against the high energy prices such as those that characterize the end of 2021. The economics of implementing an on-farm AD installation under current and potential future UK policy regimes are explored, using the Leckford Estate as an example. An economic model has been developed for this study, underpinned by AD process data from the University of Southampton's mass and energy balance model ADAT (Anaerobic Digestion Assessment Tool), available at <http://borrg.soton.ac.uk/resources/adat> (accessed on 18 January 2022). Combinations of heat and electricity tariff support levels, capital cost, and digestate value that could make farm AD projects viable are explored.

2. Materials and Methods

2.1. The Leckford Estate as Site under Study

To ensure that the situation in practice is adequately captured and the farm perspective appropriately considered, this study is based on analysing the Leckford Estate by way of an example. The estate, known as the 'Waitrose Farm', covers approximately 1600 hectares and is part of the John Lewis Partnership (JLP). In line with the ethos of Waitrose and the JLP, the estate is 'passionate about sustainable farming' [34] and the production of quality food. With an engaged, environmentally aware, and supportive management, availability of on-site wastes primarily from livestock operations and further feedstocks from diversification activities, AD is a technology that should be accessible to this and similar farm businesses.

At the Leckford Estate, an AD case study (not published) was originally carried out in 2017 by the first author of this paper. For the purpose of this current research, the situation at the Leckford Estate has been revisited because of the unique opportunity that the combined conditions under the current post-Brexit policy changes present.

2.2. Feedstock Pre-Assessment and Selection

To enable an assessment of the feasibility of AD at the Waitrose Farm, the various agricultural operations were examined to identify a range of potential digester feedstocks, their volumes, and seasonal availability.

The primary feedstock for the proposed AD installation is slurry and farmyard manure from the 550-cow Holstein/Friesian dairy herd. This herd size is larger than the UK average of 155 animals [35], the EU average of 45 [36], and the US average of 297 animals [37], although it should be noted that such average figures hide large variations in herd sizes, particularly in the US and UK.

The cows are housed for part of the year (1 November–1 April), with access to grazing for at least 120 days a year. Approximately 50 of these cattle will not be in milking, so will be housed on straw yards, producing 75% farmyard manure (FYM) and 25% slurry. The remaining 450 will be producing slurry. A further 50 cows will be in the 'dry cow yard' and will also be producing FYM during the winter housing season. In the summer, half of these will be out to grass. Of the 500 cows normally in the main accommodation shed, on average, 300 cows will spend 10 h per day at grass through this period, so 10/24 of the manure from these animals will not be collected.

Other farm operations generating waste feedstocks include free-range chickens; apple and pear orchards; grape vines; beef cattle and sheep, which are permanently out to pasture; a mushroom growing operation; and a cold-pressed rapeseed oil production facility. Further enterprises that produce small amounts of organic material include a golf course, a nursery, a farm shop, a lodge/campsite, a guest house, and a café.

In order to provide a conservative biogas production figure, control capital expenditure and minimise potential process problems, a number of potential feedstocks were excluded from the final calculation. These included feedstocks that were:

- intermittently produced after long-term in-situ storage and therefore likely to have little biogas potential;
- in quantities too small to justify the regulatory and equipment costs associated with its processing; or
- highly lignocellulosic, so less suited to AD, particularly without further processing.

Although there is an arable part of the business and energy crops could be a potential choice to underpin biogas production at agricultural AD installations [38], the John Lewis Partnership did not wish to introduce purpose-grown crops as an AD feedstock, thus maintaining their key focus on food production. Maize silage was, however, considered for inclusion as an option to improve the economic case for the digestion plant and/or level out seasonality.

2.3. AD Plant Site Selection and Request for Supplier Quotes

Before contacting potential AD plant suppliers active in the UK market, a suitable site for the plant installation was identified, based on the following main criteria: a large open area with suitable road access and proximity to the main feedstocks, existing feedstock storage, a water supply, and an electricity grid connection.

Three types of AD technology supplier were contacted to provide 'budget' quotes based on the digester location and feedstock types and volumes. These were: a supplier who designs simple cost-effective farm-based digesters (CAPL), one whose mid-range farm digester offering could provide automated de-gritting (CAPM), and a third who provides mainly industrial digesters (CAPH). As all suppliers provided quotes in British pound sterling (GBP) (£), monetary figures are shown in this currency.

Best efforts were made to ensure that the three quotes encompassed a similar scope of supply. It is important to note that, at this stage, suppliers use their own feedstock biogas production values for CHP and digester sizing. Whilst main components such as the tank and pipework, CHP container, feed system, control system, and any associated pumps will be included in a quote, many site-specific items may be approximate estimates only or may be considered out of scope at the budget quotation stage. These items could include planning, professional fees, road access, security, hardstanding, water supply, drainage, feedstock storage (e.g., silage clamps), rainwater/effluent catchment, data cabling, electricity supply, cost of electricity grid access, operator amenities, modifications to buildings or slurry/materials handling systems, permitting, compliance (e.g., bunding), commissioning

(including cost of initial heating), digestate storage, and separation equipment. Therefore, quotes received were evaluated against literature data to check for reliability and whether they were realistic.

2.4. Digester System Modelling Using the ADAT Tool

The University of Southampton's ADAT mass and energy balance modelling tool [39] was used for the digester modelling. While several biogas production models are available online and offline, the ADAT tool, developed under the leadership of the University of Southampton in the context of various academic projects and support from the IEA (International Energy Agency) Task 37 UK, has a number of advantages, such as transparency about data assumptions and calculations, inclusion of fertiliser values in the underlying database, the option to easily add feedstocks as required by the specific user case, and availability of a comprehensive manual. The ADAT tool has been used in several studies [40–43].

Feedstock volumes were entered into the ADAT model. Where specific feedstocks were not available within the model, values for total solids, volatile solids, and methane production were taken from a range of other sources and added to the model as a 'user-defined' feedstock.

Two scenarios for energy use were considered:

1. Digester with CHP electrical production only (referred to as CHP-E scenario)
2. Digester with CHP electricity production and heat use at the mushroom farm (referred to as CHP-EH scenario)

Table 1 shows the parameters used in the ADAT model for a steel construction digester with integral gas storage operating at a mesophilic temperature of 37 °C located in the Southampton climatic region. Default ADAT values [39] were used for all parameters unless otherwise indicated.

Table 1. Main parameters for the farm anaerobic digestion system from the ADAT modelling tool.

Parameter	Value	Unit
Digester organic loading rate	4.0	kg VS m ⁻³ day ⁻¹
CHP electrical efficiency	35%	
CHP heat efficiency	56%	
Load factor	8000	h year ⁻¹
Heating energy source replaced	Heating oil	L year ⁻¹
Digester operational lifespan	20	years

The ADAT modelling tool was used to calculate the total feedstock volume, the digester size based on loading rate, the retention time, biomethane production, digestate output, CHP size, CHP electricity production, digester parasitic electrical energy, and net heat output after allocating required digester heating. The ADAT model can also calculate embodied energy [39], but as the aim of the study was to establish the potential economic viability of an on-farm digestion system rather than its carbon footprint, this was not considered.

2.5. Economic Modelling

Based on the ADAT model output and the three supplier quotes, a purpose-built economic model was created in Excel to explore the economic outcomes of the two energy options (CHP-E scenario, CHP-EH scenario). The economic model integrates the following three key parameters: (1) capital expenditure; (2) energy production expectations; (income and savings); and (3) operation and maintenance costs as described below.

2.5.1. Capital Expenditure

Budget digester cost from the suppliers is the main cost element considered here. It is also possible to include other costs such as planning, grid connection, consultants, digestate

storage, groundworks, water supply, commissioning boiler fuel, permitting, and where applicable, heat meters, heat pipe, and trenching. In order to maintain a similar scope of supply and to minimise any skewing of budget costs, none of these other costs were specifically included in the economic viability calculations in the current study.

For the CHP-EH scenario, the following costs were added: heat pipe at £100 m⁻¹, pipe trenching at £8 m⁻¹ (based on Estate costs), heat meters at £1000, plus a contingency margin of 3.7% of these total costs.

2.5.2. Energy Production

Figures derived from the ADAT model were included here: gross energy production, CHP size, CHP electrical efficiency, load factor, and electricity production based on the load factor.

For the CHP-EH scenario, the following additional parameters were considered: CHP heat efficiency and heat production based on the load factor.

2.5.3. Income and Savings

In order to ascertain what savings might be achieved through electricity and heat generation, net heat and electrical energy values are calculated after deduction of ADAT-derived digester parasitic heat and electricity values, respectively. The model allows a percentage of the net electricity to be used on site to displace bought-in electricity, with the remainder exported at £0.0557 kWh⁻¹ [44]. Where excess CHP heat can be beneficially utilised on site, the model allows a percentage of heat to displace fossil fuels such as heating oil, liquefied petroleum gas (LPG), or natural gas. In this case study, heating oil was displaced.

Although the UK no longer has incentives designed specifically for heat or electricity production from biogas, historical tariff values exist, and provide an indication of the support levels that government deems practicable in terms of both budget and levels of deployment. Therefore, the model utilised selected tariff levels from the Feed-in Tariff (FIT) for electricity production [44] and the Renewable Heat Incentive (RHI) for heat production [45]. FIT levels were banded in order to provide smaller systems with greater tariff support. Between the FIT introduction in April 2010 and September 2011, these systems would have fallen into a sub-500 kWe CHP band; thereafter, they would be included in the sub-250 kWe CHP band.

The FIT tariff levels currently available [44] are higher than they were at the inception of the scheme, since they are index-linked and therefore adjusted annually in line with the UK Retail Prices Index (RPI). AD FITs for the relevant CHP capacity band were extracted and analysed for the highest (FITH) and lowest (FITL) values. To facilitate fiscal management of this fixed budget, the FIT scheme also included a degression mechanism that reduced tariffs as deployment increased, meaning that there was a significant difference between these two figures, so a median figure was also calculated (FITM).

A similar exercise was carried out to ascertain the minimum and maximum RHI tariff levels, RHIL and RHIH, respectively. Although the RHI scheme also included a degression mechanism, the differential between these two figures was not large, so a median figure was not calculated. Both tariff levels are given in Table 2.

Nutrients in digestate have a potential value because they can reduce or eliminate the need for fossil fertilisers [46]. The model calculates potential savings in fertiliser costs associated with digestate utilisation, but inclusion of these is optional since this value has historically been hard to realise.

Fertiliser values in terms of nutrients contained can be based either on ADAT figures [39] or on the RB209 farm nutrient management guide standard values for farm sourced digestate [47]. For the purposes of the case study, RB209 figures of 3.6 kg tonne⁻¹ (total N), 1.7 kg tonne⁻¹ (P₂O₅), and 4.4 kg tonne⁻¹ (K₂O) [47] were used since reliable nutrient data for the user-defined feedstocks in the ADAT model could not be ascertained.

Current market prices for equivalent fossil fertilisers were obtained [48] in order to provide a value for each kilogram of each nutrient. These fertilisers were ammonium nitrogen at 34.5% N content, triple super phosphate (TSP) at 46% P₂O₅ content, and muriate of potash at 60% K₂O content. The sum of these individual nutrient prices represents the displaced cost of synthetic fertiliser.

Table 2. Economic model parameter values.

Parameter	Value	Unit	Notes
FIT (feed-in tariff) rate	£0.0465 (FITL) £0.1104 (FITM) £0.1814 (FITH)	£ kWh ⁻¹	2021 rate, indexed. From low of £0.0465 kWh ⁻¹ (start 1 January 2019) to high of £0.1814 kWh ⁻¹ (start 30 September 2011), as well as median of £0.1104 kWh ⁻¹ [44]
Cost of electricity replaced by on-site production	£0.1361	£ kWh ⁻¹	Electricity average prices purchased by non-domestic consumers in UK [49]
RHI (renewable heat incentive) rate	£0.0309 (RHIL) £0.0873 (RHIH)	£ kWh _{th} ⁻¹	2021 rate, indexed. From low of £0.0309 Wh _{th} ⁻¹ (1 July 2017 tariff) to high of £0.0873 Wh _{th} ⁻¹ (before 1 April 2016) [45]
Cost of heating fuel replaced (diesel/heating oil)	£0.055	£ kWh ⁻¹	Converted from price per litre using net calorific value of 35.73 MJ per litre [50]
Digester operation and maintenance (O&M) costs	2.5%	Percentage of capital value	2–3% indicated in literature [51]
CHP O&M costs	£0.017	£ kWh ⁻¹ produced	Literature data available: £0.0075 to £0.014 kWh ⁻¹ [51], £0.03 kWh ⁻¹ [52]
Labour	£12.50	£ h ⁻¹	Approximately 2 h daily [53]

2.5.4. Operation and Maintenance (O&M) Costs

As outlined in Table 2, these include AD operator wages, as well as annual permitting, insurance, and rates. Digester and CHP maintenance costs are also included here.

2.5.5. Economic Viability Calculations

An internal rate of return (IRR) is calculated based on the capital cost, total income/savings, total operational/maintenance costs, and a Retail Price Index (RPI) of 102%. It is assumed that short-lived equipment will be replaced every 5 years at 4% of the original capital expenditure and that, additionally, 20% of the original capital expenditure will be spent every 10 years [23]. The IRR is calculated over 20 years.

The internal IRR target for JLP in 2017 was 16%, although, the company recognised the wider environmental benefits of projects such as an AD installation, and so was prepared to consider lower returns.

Based on the ADAT model output and the three supplier quotes, the economic model was then used to explore the economic outcomes of the two energy options (CHP-E scenario, CHP-EH scenario) with the aim of answering the following questions:

- What internal rate of return (IRR) might be achievable by adjusting subsidy levels to the historical highest (FITH), median (FITM), and lowest (FITL) FIT tariff?
- Using the highest/median/lowest FIT/RHI subsidy levels as appropriate, what capital cost is required for the digester to achieve a 16% IRR?
- What level of policy support might be required against a background of high energy prices as witnessed in 2021?

The capital cost of digesters has not historically decreased, particularly for large systems that are complex and expensive civil engineering projects. Nevertheless, precedent exists for small digesters, which are modular and off-the-shelf, with minimal expensive site work, thus reducing capital costs [21].

3. Results and Discussion

3.1. Methane Generation and Digester Design

Table 3 shows the feedstocks as entered into the ADAT model and the resultant methane production estimates; where values were not available within the model, methane yields were taken from the sources shown in the notes. Feedstocks themselves can be variable within a single farm or even within a silage clamp, for example, so some suppliers recommend lab tests be carried out to ascertain site-specific values. Feedstock characteristics for mushroom waste were estimated based on typical energetic nutritional values for raw mushrooms with a 50% reduction for spoilage to give a conservative estimate of methane yields. Thus, this waste accounted for approximately 1.4% of the total methane production. For regulatory purposes, all feedstocks are likely to be considered as wastes, thereby meeting incentive scheme sustainability criteria, although interpretation across different schemes varies in practice.

Table 3. Potential AD feedstocks and corresponding methane production.

Feedstock	FM (tonnes year ⁻¹)	Seasonal/Variable?	Notes	TS (in % of FM)	VS (in % of TS)	CH ₄ (m ³ tonne ⁻¹ VS)	CH ₄ (m ³ year ⁻¹)
Dairy cattle slurry ¹	8017	Yes	Cattle out in April to October; dairy and heifer units	9%	83%	185	110,792
Farmyard manure (FYM) ¹	4432	No	High straw content; batch mucking out; dairy and heifer units. Chopped straw recommended.	25%	80%	190	168,412
Mushroom stalks and waste mushrooms	568	Yes	Supply and demand variable	8%	85%	135	5217
Rapeseed press cake and filter waste ¹	157	No	Some could be used as cattle feed or potentially sold off as feed	90.3%	94.7%	430	57,777
Waste milk	109	Yes	Variable depending upon calving and cattle illness; standard literature value [54] ²	13.5%	94.7%	564.6	7903
Waste silage (feed) ¹	104	Yes	Cattle out in summer	30%	94%	350	10,292
Orchard Fruit (mainly apples, some pears)	30	Yes	Seasonal, currently left on trees and/or left to fall; figures based on Dubrovskis and Plume [55]	14.53%	96.75%	451	1902
Grass cuttings from golf course and grounds	14	Yes	KTBL [56]	50%	85%	300	1785
Maize silage	Optional	No	Possible addition to levelise seasonality	30%	94%	350	variable
TOTAL ³	13,432						364,080

¹ Default ADAT values used; ² Figure refers to whole milk (as reported by LfL [54] for “Vollmilch, Kuh, Frisch”, English translation: whole milk, cow, fresh); ³ Without maize silage.

Cows are bedded on 1.5 tonnes day⁻¹ of a paper pulp/sawdust product, which has a dry matter content of 95%. Whilst both paper [57] and paper sludge [58] can produce biogas, production from sawdust is negligible [59], so a conservative assumption was made that no additional biogas was produced from the bedding.

Dairy farm substrates (slurry, FYM, waste milk and waste feed) from the 550-cow herd contribute to 82% of the yearly methane production. In the UK, approximately 1.5% of the UK’s holdings house 12.3% of the nation’s dairy cows in herds greater than 499 cows [35]. Initial targeting of larger dairy farms (such as Leckford Estate) to improve slurry management by the introduction of AD makes logistical and financial sense, particularly where they are also able to utilise local substrates such as chicken manure in case that the farm may not have a land base sufficient to spread those nutrients.

Volumes of the following feedstocks vary throughout the year at the Leckford Estate:

- Mushroom stalks and waste mushrooms—vary due to supply and demand;
- Fruit—apples and pears. Depending upon variety, harvesting can be from August through to November;
- FYM—slightly seasonal in that more is produced in the winter housing period than in summer when cows are primarily living outdoors;
- Waste silage—less silage is available in summer when the cows are grazing in fields;
- Grass cuttings from the grounds and gardens are produced primarily between April and October and are dependent upon weather, grass type (i.e., lawn/rough meadow grass), and mowing frequency.

The seasonality of these feedstocks does not affect the biomethane production calculations, as these are on a yearly basis. However, when planning such a scheme, the estate may need to consider the costs and benefits of strategies such as storage or ensiling in order to include them in a way that maintains the relatively consistent gas production that a CHP requires.

For completeness, it is noted that some potentially available biomass types were not included in the calculation due to small quantities/unreliable availability, poor quality of material (i.e., too old), or low suitability for AD (e.g., strongly lignocellulosic biomass), thus relying on conservative figures to avoid any overestimation of the methane generation to be expected. The following potential feedstocks were not included:

- Spent mushroom compost (SMC) (86 tonnes year⁻¹)—highly lignocellulosic material, and trials indicate some biogas production [60,61]. However, following a conservative approach, it was decided not to include this material due to its high straw content.
- Poultry litter (400 tonnes year⁻¹)—litter is removed from the sheds on an annual basis, so it is likely to be significantly degraded. This is from egg laying hens, so it also contains an appreciable amount of grit, which can cause silting in many types of digesters.
- Tree/bush prunings (20 tonnes year⁻¹) and leaf litter (50 tonnes year⁻¹)—woody materials and therefore not ideally suited to AD [62].
- Food waste—local food waste from a restaurant, several houses, a café, and a campsite could be included, and generally is a suitable AD co-substrate [63]. However, a collection round would need to be established and such materials would need to be shredded, pasteurised, and likely sieved to remove plastics [64]. This would add considerable cost and the volumes did not currently justify this.

Although these materials were not included in the following calculations, it is worth noting that with an operational digester, the first two feedstocks could also be trialled in order to level seasonal feedstock fluctuations.

To ensure proximity to the bulk of the feedstocks, the AD site selected was on the dairy unit, adjacent to silage clamps, two digestate storage lagoons, a holding tank, a separator, and with good road access. The site was approximately 2 km from the mushroom farm where CHP heat could potentially be utilised year-round.

Based on the above quantities of feedstocks included in the assessment, Table 4 summarises the results from the ADAT tool that were utilised in the economic modelling.

The on-site baseload electricity usage, as reported by Leckford Estate (figures not provided as commercially confidential), comfortably exceeds that of the potential CHP electrical production so all electricity could be used on site continuously. It was also confirmed that the mushroom farm could utilise 100% of the heat produced year-round: this is unusual, but many farms have a heat requirement for agricultural or diversification activities [65,66]. This is discussed further in the CHP-EH scenario below.

Table 4. Resultant ADAT model data (to be further utilised for the economic modelling).

Parameter	Value	Unit
Daily feedstock input	36.8	tonnes day ⁻¹
Digester size	1524	m ³
Retention time	31.9	days
Biogas production	609,796	m ³ year ⁻¹
Methane production	364,083	m ³ year ⁻¹
Volatile solids (VS) destroyed	744	tonnes year ⁻¹
Digestate	12,688	tonnes year ⁻¹
CHP electrical capacity	145	kWe
CHP electricity production (gross)	1157.9	MWh year ⁻¹
Digester parasitic electrical energy consumption	77.4	MWh year ⁻¹
CHP heat (net) available after digester heating	1353.7	MWh year ⁻¹
Digester parasitic heat energy consumption	499	MWh year ⁻¹

3.2. Capital Cost

Supplier quotes received to install the AD plant at the site under study were £900,000 (CAPL), £1,400,000 (CAPM), and £1,600,000 (CAPH). It was assumed that the farm would provide 100% of the funding without applying for bank loans. If finance through bank loans were required, as is likely to be the case for many typical UK farm businesses, the business case would be further detrimentally affected, and thus the assumption of no bank loan is in line with this study's approach to analyse whether economic viability of AD is at all possible.

Despite the fact that suppliers were contacted with a detailed set of data describing the specific case, it is important to note that they will use their own procedures to frame the AD plant sizing and to estimate the site-specific requirements, and these assumptions might be rather complete or not, depending on the level of detail and the degree of complexity a supplier is ready to include. In general, the cost of such site-specific items means that the actual capital cost of an AD plant installation varies greatly because the assumed complexity of the scope of the project varies: for example, a project with a complex planning application where a road, extensive bunding, and several silage clamps are included as part of the AD plant finance figure will be considerably more expensive than one of the same size where these are not required. Additionally, data on costs and their breakdown are often not readily available, as they are considered to be commercially sensitive information.

Because of this uncertainty around digester costs, quotes were cross-checked against two sources that provide UK digester historical cost data, albeit based on relatively small sample sizes. The first was a tool developed by the World Biogas Association, based on actual historical costs for 64 UK plants [67]. Quotes were also checked against the relevant CHP capacity band for low, central, and high digester cost cases analysed by Parsons Brinckerhoff in a 2015 report to the UK government [68].

The costs indicated by the obtained supplier quotes for a system based on a 145 kWe appeared broadly in line with the central and high Parsons Brinckerhoff historical costs shown Table 5. In this context, it is interesting to note that the digester cost model developed by the World Biogas Association [67] suggests that a plant of 145 kWe is likely to have a cost of £449,500; but the relatively small number of digesters analysed at this scale may account for the lack of alignment with the supplier quotes.

Thus, the three supplier quotes (capital costs of £900,000, £1,400,000, £1,600,000) obtained for the site under study are considered realistic, indicating a lower-cost solution for a simple cost-effective farm-type digester (CAPL), a medium-cost solution (CAPM), and a solution at industrial standard with elevated costs (CAPH). These figures are therefore used in the following as a basis for the economic viability calculations.

In addition, for the scenario with heat valorisation, with the mushroom farm located 2 km from the proposed digester site, the capital cost of providing heat to the farm was calculated to be £225,000 (assumptions are documented in Section 2).

Table 5. Literature-based data indicating capital costs for a range of digester sizes (derived from figures available in [68]) and, thus, calculated capital cost for a 145 kWe plant (PBL: Parsons Brinckerhoff Low Case figure; PBM: Parsons Brinckerhoff Central Case (i.e., median) figure; PBH: Parsons Brinckerhoff High Case figure).

Capacity Band	Low Case	Central Case	High Case
<250 kWe	£3780 kWe ⁻¹	£5953 kWe ⁻¹	£8126 kWe ⁻¹
145 kWe plant	£548,100 (PBL)	£887,206 (PBM)	£1,211,060 (PBH)
250–500 kWe	£3685 kWe ⁻¹	£5804 kWe ⁻¹	£7922 kWe ⁻¹
>500 kWe	£2835 kWe ⁻¹	£4465 kWe ⁻¹	£6095 kWe ⁻¹

3.3. Economic Viability of the AD Plant with CHP Electrical Production Only (CHP-E Scenario)

Table 6 shows the IRR based on the three capital expenditure levels given by suppliers. The £900,000 digester (CAPL) would easily reach the 16% IRR under levels FITM (median feed-in-tariff applicable for UK situation) and FITH (highest feed-in-tariff applicable for a UK situation).

Table 6. Internal rate of return (IRR) based on three quoted capital expenditure levels (supplier quotes obtained for the site under study), electricity production only (CHP-E scenario).

	IRR with FITL ¹	IRR with FITM ²	IRR with FITH ³
CAPL	13.57%	22.76%	32.55%
CAPM	4.45%	12.14%	19.36%
CAPH	1.66%	9.35%	16.13%

¹ FITL: £0.0465 kWh⁻¹ (lowest electricity feed-in-tariff applicable for UK situation); ² FITM: £0.1104 kWh⁻¹ (median electricity feed-in-tariff applicable for UK situation); ³ FITH: £0.1814 kWh⁻¹ (highest electricity feed-in-tariff applicable for UK situation).

Because of their broad alignment and inclusion in UK Government AD viability calculations, the calculations were repeated using the Parsons-Brinckerhoff cases [68], shown in Table 7. Due to the slightly lower capital costs, the model showed an increased IRR in all use cases.

Table 7. Internal rate of return based on historical Parsons Brinckerhoff figures (as available in [68]), electricity production only (CHP-E scenario).

	IRR with FITL ¹	IRR with FITM ²	IRR with FITH ³
PBL	25.4%	39.63%	54.92%
PBM	13.32%	23.15%	33.07%
PBH	6.85%	15.33%	23.20%

¹ FITL: £0.0465 kWh⁻¹ (lowest electricity feed-in-tariff applicable for UK situation); ² FITM: £0.1104 kWh⁻¹ (median electricity feed-in-tariff applicable for UK situation); ³ FITH: £0.1814 kWh⁻¹ (highest electricity feed-in-tariff applicable for UK situation).

These figures provide an indication of where a positive business case may lie for such systems. The capital cost of £1.2 million (PBH) to £1.4 million (CAPM) combined with the mid-range FIT of £0.1104 kWh⁻¹ appears to provide IRRs large enough to warrant investment, but not so large as to create a ‘boom’ in construction activities.

Aligning historical deployment data with FIT levels at small-scale could shed further light on where an economic FIT level might lie, but this analysis is complicated by several factors:

- There is typically a lag time between the announcement of a FIT level and a digester being commissioned. Due to the long lead-in times (typically a year or more) required for financing, planning, and constructing a digester, the UK FIT scheme had a preliminary accreditation mechanism that allowed applicants to ‘lock in’ at a given tariff level in order to provide certainty of income, and therefore make a project financially

attractive to lenders. Thus, a digester could have locked into a tariff of $\text{£}0.16 \text{ kWh}^{-1}$ on a certain date, but by the time the digester was actually built and included in deployment figures a year later, the tariff on that date could have been much lower.

- The scheme had several breaks [69], which included a ‘fast track’ tariff review and the temporary removal of preliminary accreditation, which caused breaks in digesters being commissioned.
- It is difficult to identify these smaller systems in the aggregated total deployment of all system sizes.

The average FIT level has undergone considerable changes during its lifetime [69]. While the average FIT for an AD plant of the scale 146 kWe was above $\text{£}0.10 \text{ kWh}^{-1}$ in the years 2010 to 2015, it fell to lower levels in later years, and was below $\text{£}0.06 \text{ kWh}^{-1}$ in the years 2018 and 2019. In any case, when the FIT had dropped to less than $\text{£}0.05 \text{ kWh}^{-1}$, the UK’s Anaerobic Digestion and Bioresources Association (ADBA) noted in its April 2017 policy report [70] that the smaller-scale end of the market ‘has been decimated’, adding in the November 2017 report [71] that only 13 plants under 250 kWe had been commissioned in 2016. This coincided with the timing of the original case study carried out for JLP in 2017 (report not published), which concluded that the desired IRR could not be achieved at the more realistic CAPM and CAPH levels using these parameters: a FIT rate of $\text{£}0.0499 \text{ kWh}^{-1}$, an RHI rate of $\text{£}0.0226 \text{ kWh}_{\text{th}}^{-1}$, and energy prices of $\text{£}0.10 \text{ kWh}^{-1}$ and $\text{£}0.42 \text{ kWh}^{-1}$ for electricity and heating oil, respectively.

The 1 April 2015 FIT was set at $\text{£}0.1013 \text{ kWh}^{-1}$, which when modelled using current energy prices, provides an IRR in double figures for all cases except CAPH; this therefore provides a further clear indication of the level of support below, for which few plants of this size are likely to be built.

3.4. Economic Viability of the AD Plant with CHP and Heat Use (CHP-EH Scenario)

In the case of the site under study in this research, the mushroom farm is able to use all of the CHP heat produced year-round, and thus full valorisation of the available heat is assumed. This represents a best-case setting with view to heat usage. The improved IRRs under this setting, shown in Table 8, reflect the financial benefits of utilising both heat and electricity.

Table 8. Internal rate of return based on three quoted capital expenditure levels, electricity production and 100% heat use (CHP-EH scenario).

	IRR with FITL ¹		IRR with FITM ²		IRR with FITH ³	
	RHIL	RHIH	RHIL	RHIH	RHIL	RHIH
CAPL	21.83%	29.20%	28.61%	35.73%	36.27%	43.25%
CAPM	13.00%	18.75%	18.30%	23.62%	24.02%	29.08%
CAPH	10.54%	15.97%	15.55%	20.48%	20.84%	25.47%

¹ FITL: $\text{£}0.0465 \text{ kWh}^{-1}$ (lowest electricity feed-in-tariff applicable for UK situation); ² FITM: $\text{£}0.1104 \text{ kWh}^{-1}$ (median electricity feed-in-tariff applicable for UK situation); ³ FITH: $\text{£}0.1814 \text{ kWh}^{-1}$ (highest electricity feed-in-tariff applicable for UK situation).

Overall CHP efficiency is increased if a beneficial heat use can be found. It is easier to use the bulk of the heat produced by a smaller CHP, thus maximising the overall system efficiency. Leckford Estate is relatively unusual in its ability to utilise heat year-round. Nevertheless, a dairy farm could use CHP heat for hot water in buildings [65,66], for dairy washing (which is a highly relevant cost factor for dairy farms, typically amounting to nearly one third of electricity costs of a dairy unit [72]), space heating, crop drying, and to improve milk yields by warming cattle drinking water [73,74]. A number of increasingly common farm business diversification activities also use heat, e.g., greenhouses, campsites (space and water heating), and local food production operations.

A FIT tariff of $\text{£}0.1013 \text{ kWh}^{-1}$ has historically resulted in modest digester deployment. In a scenario where 70% of the heat could be used, it was decided to calculate what level of

RHI support would be required in order to achieve an IRR of 16% at CAPM and CAPH. This resulted in an RHI rate of $\text{£}0.0459 \text{ kWh}^{-1}$ and $\text{£}0.0859 \text{ kWh}^{-1}$ at CAPM and CAPH, respectively. This result is broadly in line with the RHIL of $\text{£}0.0309 \text{ kWh}_{\text{th}}^{-1}$ and RHIH of $\text{£}0.0873 \text{ kWh}_{\text{th}}^{-1}$, a level of support which has historically been considered reasonable.

With the end of the FIT in April 2019, electricity generation from biogas has fallen from regulatory favour, not least because the bulk of the energy produced from even the most electrically efficient CHP is in the form of heat. In the UK and countries with similar climates, it is relatively rare to find a year-round heat use, nevertheless, system economics can be improved by utilising a greater proportion of the CHP heat production. Particularly in colder climates where there is a much wider variation in the heat demand, not least for digester heating, the challenge is to ensure that there is sufficient heat produced to meet the demand. This means that in seasons of low demand, there is a greater excess of heat. Strategies to address this might include finding a further seasonal heat use, for example, a diversification activity such as hot water for campers. Conversely, any seasonal shortfall could be met through other renewables: biomass, solar PV, solar thermal, battery storage [75].

3.5. Analysis of the Impact of Energy Prices

In view of the recent sharp increases in energy prices across the UK and worldwide, it was decided to explore the potential for subsidy free support for the production of electricity while utilising 70% of the heat. Table 9 illustrates what electricity prices (required non-domestic prices) would have to be in order to achieve economic viability of an AD plant at the studied site, and includes a less ambitious IRR of 10% in a subsidy-free scenario where CHP heat is replacing heating oil (at a cost of $\text{£}0.55$ per litre [50]).

Table 9. Minimum economic electricity prices at varying capex and IRR under a tariff-free regime with 70% heat use.

	Electricity Price Required (Pence kWh^{-1} Electricity Sold) to Achieve Economic Viability of the AD Installation			
	Electricity Usage Only		Electricity and Heat Valorisation ¹	
	At 10% IRR	At 16% IRR	At 10% IRR	At 16% IRR
CAPL	16.76	20.57	14.92	19.62
CAPM	23.39	29.37	21.59	28.49
CAPH	26.1	32.89	24.26	32.01

¹ Replacing heating oil with an average price of $\text{£}0.055 \text{ kWh}^{-1}$ [50].

With an average non-domestic electricity price for very small non-domestic users of $\text{£}0.1734 \text{ kWh}^{-1}$ over the period from the fourth quarter (Q4) of 2019 to the second quarter (Q2) of 2021 [49], future electricity prices in the region of approximately $\text{£}0.20 \text{ kWh}^{-1}$ seem increasingly likely, which would make some scenarios an economic proposition.

These figures [49] show a gradual increase in non-domestic electricity prices from an average of $\text{£}0.0416 \text{ kWh}^{-1}$ in 2004 to $\text{£}0.1361 \text{ kWh}^{-1}$ in Q2 of 2021, an increase of 327%, with natural gas rising from $\text{£}0.01254 \text{ kWh}^{-1}$ to $\text{£}0.0259 \text{ kWh}^{-1}$, an increase of 207% over the same period. These figures do not reflect the steep rise in wholesale gas prices experienced in the last quarter of 2021 [76]. Due to worldwide increases and volatility in the wholesale gas price market, UK prices reached as high as $\text{£}0.042 \text{ kWh}^{-1}$ [77], affecting both gas and electricity prices (as 35.7% of electricity is generated using gas [78]).

Support at the lowest FIT rate of $\text{£}0.1013 \text{ kWh}^{-1}$, coupled with the lowest RHI rate at $\text{£}0.0309 \text{ kWh}^{-1}$, an electricity price of $\text{£}0.1492 \text{ kWh}^{-1}$ and $\text{£}0.1840 \text{ kWh}^{-1}$ at CAPM and CAPH, respectively, would provide an IRR of 16%. These values are greater than the ten-year (2010 to 2019) non-domestic electricity price average of $\text{£}0.1030 \text{ kWh}^{-1}$. However, the value of $\text{£}0.1492 \text{ kWh}^{-1}$, although higher than the current average electricity price modelled of $\text{£}0.1361 \text{ kWh}^{-1}$, is certainly within the range of 3rd quarter 2021 prices for small/medium users ($\text{£}0.1502 \text{ kWh}^{-1}$ for 500–1999 MWh annual usage) and less than

that for small users (£0.1534 kWh⁻¹ for 20–499 MWh annual usage) and very small users (£0.1818 kWh⁻¹ for 0–20 MWh annual usage) [49]. This provides a further indication of the support required if the general trend for average non-domestic electricity prices continue their gradually increasing trajectory, which has characterised the past seventeen years (2004–2020) [49].

UK domestic electricity prices are typically higher than the European average, whereas gas prices are lower [79,80]. This price differential when coupled with the poor building fabric tends to discourage electrification, and therefore the decarbonisation of heat, particularly in rural areas where electricity grids may be weak and there is no access to the gas grid for alternative fuels such as hydrogen. In the face of climate change perturbations and the complexity associated with fossil energy market forces, it is unclear whether such volatility will continue [81], since multiple factors such as supply chain issues, energy systems decarbonisation, and emissions trading scheme carbon prices affect costs [76].

Where energy costs are both high and volatile over a long period, on-site de-centralised energy generation becomes particularly important and AD at small scale using mainly wastes becomes increasingly viable, cushioning these important farm businesses against such volatility and helping the UK and other countries meet their COP26 Methane Pledge and wider climate goals.

However, unless there is a guarantee that prices will be sustained at such levels, AD projects are still unlikely to be considered worthy of investment, so some form of support for technology implementation would still be required, e.g., a minimum price guarantee or floor price. Energy based incentives which also value the non-energy contributions of AD to such farms could be an option [7,82]. These could, for example, combine a small-scale electricity/heat tariff to improve on-site/local energy utilisation. There is an added opportunity to consider the benefits of AD in the context of the post-Brexit agricultural policy support schemes.

3.6. Digestate Savings/Income

The value of digestate as a source of nutrients that can displace fossil fuel based synthetic fertilisers (which can be costed) and as a soil conditioner, which replenishes soil carbon (which is difficult to cost) was not taken into account in any of the above calculations. Digestate is often regarded as an expense to the business, particularly for large digesters where large volumes of digestate require longer transport distances in order not to cause soil nutrient overloading [83]. Whilst the ADAT tool can include the energetic cost of transport, this was not included within this economic case study, as digestate was not being transported any further than the slurry and wastes otherwise would have been.

Digestate can also be separated into liquid and solid fractions to facilitate differential nutrient application [16]. Prior to the introduction of end of waste criteria, digestate fibre mixes used to be sold to gardeners [21] as a peat-free option, but the costs now associated with meeting the requirements [84] are likely to preclude small digesters from this market, unless costs could be defrayed through, for example, an aggregation mechanism whereby several smaller operations could be considered as one for the purposes of regulation.

Against a backdrop of high fossil fuel energy prices, the value of digestate can offset the commensurately high price of fossil fertilisers [48]:

- Nitrogen—34.5% Ammonium Nitrate—£616 tonne⁻¹
- Phosphate (P₂O₅)—46% Phosphate TSP—£525 tonne⁻¹
- Potash (K₂O)—60% Muriate of Potash—£534 tonne⁻¹

Using the above fertiliser costs [48] and RB209 nutrient guide values [47], a tonne of digestate was calculated to be worth £9.39 or a total of £119,160 in this case study, potentially further improving the economics of the project under study. For a CAPM RHI digester using 70% heat with no subsidies and digestate at this price, the IRR is a respectable 12.76%.

The results thus confirm previous reports that recycling such organic materials back to land in the form of digestate can potentially add value [33,53] while improving the GHG credentials of the business [75,85].

The post-Brexit agricultural policy aims to reward public goods, particularly those related to the environment [86,87], including improved soil health, water quality improvement, and reduced GHG emissions. A well-run AD plant that recycles carbon back to soils as digestate and captures or avoids otherwise uncontrolled emissions occurring from biodegradation of organic matter or storage of materials (particularly methane from slurry stores) can contribute to these aims [1] and as such should be recognised within that policy [4].

4. Conclusions

As illustrated in this research, small farm-scale AD installations that utilise diffuse on-site or locally sourced wastes to produce both electricity and heat from a CHP can improve the overall efficiency and economics over those that do not valorise the heat. Additionally, they can provide heat at a scale that can often be beneficially utilised. AD can help cushion such food production businesses against high and/or volatile energy prices, as well as helping to decarbonise a sector that often uses carbon intensive fuels for heating. Where rural electricity grids are weak and/or electricity is expensive, on-site electricity production also provides a route to farm business electrification, increasing economic options for utilisation of electrical vehicles, agritech, robotics, and more.

The Leckford Estate is a large, diversified farming business owned by a major retailer with a commitment to sustainability and access to a wide range of local waste feedstocks, but under the current UK policy regime, which is characterised by a lack of support at this relatively small scale (145 kWe, 1500 m³ digester), it is uneconomic for the estate to utilise these resources through AD in order to reduce its carbon footprint and improve their sustainability in the face of climate change.

As energy prices increase, the required level of support for such projects decreases, but projects also struggle to put an economic business case together where there is no long-term pricing clarity or alternative support mechanisms that value the many benefits of AD. The results of the current study can be used to provide an indication of recommended levels of support, and a basis for varying them in response to shifting energy prices.

Designing a policy that values these benefits is a challenge for all countries and regions [33], but with the introduction of a new agricultural policy, the UK has an opportunity to valorise these diffuse organic wastes through small AD, and support farm businesses in the face of the urgency of the climate crisis and high energy prices.

One potential support mechanism could be to include the ‘public goods’ benefits of on-farm AD (including greenhouse gas reduction, improved nutrient management, positive soil organic carbon impact, and strengthened rural development) in the UK post-Brexit agricultural policy support scheme.

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