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The Role of Anaerobic Digestion in reducing Dairy Farm Greenhouse Gas emissions

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Abstract: Greenhouse Gases (GHG) emissions from dairy farms are significant contributors to global warming. However much of the published work on GHG reduction is focused on either Methane (CH_4) or Nitrous Oxide (N_2O), with few, if any, considering the interactions that changes to farm systems can have on both gases. This paper takes the raw data from a year of activity on a 300 cow commercial dairy farm in Northern Ireland to more accurately quantify the GHG sources by use of a simple predictive model based on IPCC methodology. Differing herd management policies are examined together with the impact of integrating Anaerobic Digestion (AD) into each farm system. Whilst significant success can be predicted in capturing CH_4 and Carbon Dioxide (CO_2) as biogas and preventing N_2O emissions, gains made can be lost in a subsequent process negating some or all of the advantage. The process of extracting value from the captured resource is discussed in the light of current farm parameters together with indications of other potential revenue streams. However, this study has concluded that despite the significant potential for GHG reduction, there is little incentive for widespread adoption of manure based farm scale AD in the UK at this time.

Keywords: Climate Change; Greenhouse Gas Emissions; Methane; Nitrous Oxide; Cow Manure; Anaerobic Digestion.

1. Introduction

Driven by visible evidence of climate change all around us, the concept of sustainability is influencing political and socio-economic choices with International effort focused on targets to reduce greenhouse gas (GHG) emissions. Signatories to the 2015 Paris agreement [1] have committed to holding the global temperature increase to well below 2°C above pre-industrial levels and pursue efforts to limit the increase to 1.5°C in a manner that does not threaten food production. Many countries including the UK and the member states of the European Union have since committed to targets of being climate neutral or net zero by 2050. As part of this effort, it is widely accepted that controlling climate change will not be achieved until the levels of GHG emissions are substantially reduced. Whilst Carbon Dioxide (CO_2), the most prevalent long-lived greenhouse gas is the main contributor, substantial progress can be made in slowing the rate of near term climate change by tackling the three principal Short Lived Climate Forcer (SLCF), pollutants of methane (CH_4), black carbon, and tropospheric ozone (O_3) [2] alongside actions on CO_2. As CH_4 is the second most common GHG emitted from human activity, this gas is deserving of special focus.

CH_4 despite a short 12.4 year atmospheric lifetime has a Global Warming Potential (GWP_{100}) 28 times greater than CO_2 [3] and is the primary precursor gas of tropospheric Ozone that absorbs radiation to become a strong greenhouse gas in the near atmosphere. Taken together this makes CH_4 the most influential GHG after CO_2 and the relatively short lifetime means controlling this gas can yield benefits quickly. By contrast, Nitrous Oxide (N_2O) is a long-lived GHG that has a GWP_{100} of 265 times that of CO_2 and an atmospheric lifetime of 121 years [3] making it a much more persistent cause of climate change that is harder to halt and reverse.

1.1 The context of Livestock Farming

Food production is a sequence of complex biological processes involving multiple GHG interactions from CO_2 and N taken up by growing crops, carbon sequestration in soils, CH_4 emissions from livestock, their manures and flooded rice paddies to N_2O emissions from fertilised land. Amongst all of the data surrounding the sector, the most prominent are the emissions from the global livestock sector have been estimated to contribute 14.5% of all human induced GHG emissions [4]. The main gases emitted from this sector were CH_4 44%, N_2O 29%, CO_2 27% yet whilst emissions varied by sector and region, emissions from cattle producing beef and milk were significantly greater than any other species. In regions where animal fodder quality was poor, the emissions were greater and productivity levels lower indicating the importance of animal diet in controlling emissions [4].

Most CH_4 from livestock is a by-product of enteric fermentation, largely from ruminant animals (e.g. cattle, sheep, goats), as carbohydrate is digested in the animal gut. Significant quantities are also released as methanogenic bacteria degrade the organic fraction of manure under anaerobic conditions. A study in the Netherlands [5], showed enteric fermentation is the most important source (approx. 80%) of CH_4 in dairy husbandry, whereas most CH_4 (>70%) on pig and poultry farms originates from manures. By comparison N_2O is mainly emitted from fertilised land with additional contribution from aerobic storage and treatment of manures. An estimate of N_2O emissions in UK [6] showed that the main sources (approx. 62%) originate from the soil sector by nitrogen (N) fertiliser and animal manure applications to land and urine deposited by grazing animals. A further 26% is attributed to leaching and runoff, whilst the remainder is from animal waste management. Of the soil sector 77% emissions are from fertiliser, 17% from applied manures and 5% from grazing animals.

Animal derived CO_2 is considered biogenic by returning to atmosphere CO_2 that was captured by plant photosynthesis, however anthropogenic CO_2 that is derived from burning fossil fuels and decomposition of lime applied to pasture are counted in the emissions tally. Ammonia (NH_3) that is not a recognised GHG is also worthy of mention as it can become an indirect source of N_2O in the atmosphere. In a Europe wide survey [7], soil based NH_3 emissions from fertiliser application and grazing were lower than NH_3 emissions from housing and storage that is the opposite for N_2O.

Manure, that is an inevitable by-product of livestock farming, can become a major source of air and water pollution during organic decomposition. CH_4 is released when manure is handled under anaerobic conditions, while the formation of N_2O requires aerobic conditions with access to oxygen. As such GHG and NH_3 can be produced and emitted at each step of the manure management process from generation by livestock, to collection, storage and culminating with manure spreading to land [8] meaning a whole system approach is required if emissions are to be successfully curtailed, such that savings in one area are not lost in another.

On intensive farms, that commonly do not use bedding materials, the slurry formed by the mix of faeces and urine remains in a predominantly anaerobic state and CH_4 dominates. In these slurry-based systems, NH_3 losses from concrete yards are also significant and have been estimated to generate almost 10% of UK & Ireland NH_3 emissions [9]. Frequently removing manure from animal houses helps reduce this loss and has also been shown to decrease emissions of CH_4 by 55 ± 5% and N_2O by 41 ± 17% [10]. In most European countries, and as a result of the EU Nitrates Directive, farms will have sufficient manure storage to span the winter months. At low temperatures, commonly found in outdoor storage especially in winter, CH_4 production is reduced and has been shown to be not significant below 15°C [11]. Modelling has predicted that cattle slurry CH_4 emissions can be halved by reducing the temperature in slurry channels or by daily emptying to an outside store [12]. Consequently, indoor storage and especially that found in houses with slatted floors and slurry pits underneath are likely to have very significant CH_4 losses.

The final phase in the process is field application that is responsible for most of the odour release and is the phase where nutrients get returned to the soil for uptake by growing crops. Application methods that minimise contact of manure with air tend to have lower NH_3 emissions with direct injection seeing a reduction of 73% and trailing shoe by 57% on grassland [13], whilst [14] found N_2O losses were 20-26% lower with trailing hose than injection. In a study of application by low level trailing hose it was noted that at this stage emissions are dominated by N_2O (74-83%), followed by

NH_3 (15-24%) and CH_4 (2-3%), with most release of NH_3 and CH_4 in the hours and days after application [15].

1.2 Anaerobic Digestion

Anaerobic Digestion (AD) has been widely adopted to reduce the polluting effects of sewage and food waste from industrial processes but is a lesser-used pollution reducing technology in the agricultural sector. AD is a natural process that when carried out in a controlled environment enables the ensuing biogas to be captured and used to replace fossil fuels. Biogas is dominated by CH_4 (50-70%) and CO_2 (30-50%) with Hydrogen Sulphide (H_2S) also present in biogas from animal slurries. The bulk of the energy content of the material undergoing degradation is conserved in methane with only a minor fraction used for bacterial growth and reproduction [16], whilst CO_2 has no associated energy. Comparatively, purpose grown energy crops have a higher biogas potential than manure slurries from which the animal has extracted much of the energy from the original food but slurry does have a positive effect on process stability by contributing a high content of trace elements [17]. Difficult to digest carbon is returned to soil locked in the compounds of the digestate whilst nitrogen loss through volatilisation to NH_3 or N_2O is prevented due to the gas tight environment. In high Nitrogen feedstocks such as grass silage or chicken litter, Ammonium can be an inhibitor to the digestion process but managed correctly Ammonium Nitrate (NH_4NO_3) concentration is increased raising the plant available nitrogen content of the digestate. In 27 months of AD operation a 19% increase [18] in NH_4NO_3 was observed compared to raw slurry that when applied to land reduced the quantity of inorganic fertiliser required.

An April 2020 EU report [19] looking at the contribution Agriculture can make to the EU's 2030 GHG emission reduction target used the Common Agricultural Policy Regional Impact Analysis (CAPRI) model that considered measures targeted towards the Crop and Livestock sectors. Within the Livestock sector, underlying assumptions from the International Institute for Applied Systems Analysis (IIASA) GAINS model [20] were used; specifically Farm Scale Anaerobic Digestion, Changes to animal diet (low nitrogen feeds and methane inhibiting additives), Genetic improvements (to increase dairy milk yield and improve ruminant feed efficiency) and Vaccination against methanogenic bacteria in the rumen.

The report [19] indicated the greatest reduction was found to be from maximum application of Anaerobic Digestion of cattle and pig manures on farms of over 200 Livestock Units across the EU-28, (-12.7 Mt CO_2eq), closely followed by linseed as feed additive (-10.6 Mt CO_2eq). The reduction of GHG resulted from effectiveness and implementation share, which for AD across all member states was 35% (with UK at 14% and Ireland at 8%). The report classified AD as a high mitigation, relatively low cost technology whereas linseed feed additive was classed high mitigation with high cost. The relatively low implementation rate of AD in UK / Ireland occurs in part due to the focus on the larger farms that are more likely to be able to afford the technology and a higher prevalence of summer pasture grazing.

Year round confinement is uncommon in UK and Ireland where grass based dairy systems predominate with 80-95% and 95-100% respectively of herds grazing pasture [21] compared to less than 50% for Central Europe (Denmark, Germany, Austria) and closer to 20% for Southern Europe (Spain, Greece, Italy). With animals out grazing, much of the manure gets deposited in fields and only a small proportion is collected at milking times. For AD, that is a continuous process, this presents a barrier to more widespread adoption. As manure based AD captures most CH_4 and achieves the best environmental outcome when fed regularly on fresh manure that has not had time to degrade [22, 23] it would not be efficient to store winter produced slurry for use during the grazing season. Therefore, the potential size of any system on a pasture farm will be limited by availability of slurry collected during the grazing season, unless another feedstock is available. Co-digestion of maize silage and animal slurry as an AD feedstock is well proven, but in regions with less favourable weather conditions growing this crop can cause issue at planting or harvest and there may also be a negative Land Use Change (LUC) impact from soil carbon losses if converting former grassland into

cropland. Grass silage, although of lower energy value than maize, is easier to integrate into a pasture based farming system and has been shown to be a suitable alternative under Irish conditions [24].

Upon departing the digester, it has been shown that digestate continues to release significant quantities of gas. In a Canadian study [25] of open storage, CH_4 emissions amounted to 12% of biogas collected inside the reactor whilst a Swedish study [26] noted 3 times higher CH_4 emissions from digestate than raw slurry from storage over the summer months.

Although AD can occur as a wet or dry process, the majority of plants use wet fermentation that allows for continuous treatment, and is a good fit with the slurry disposal needs of intensive livestock farms. In Europe, the most common reactor configuration seen in agriculture is the Mesophilic Continuously Stirred Tank Reactor (CSTR) that is best suited to substrates of between 2-12% DM [16]. Inside the CSTR, the AD process is dependent on mixing to create a homogenous mixture that keeps solids in suspension, whilst distributing microorganisms, inoculating fresh feed and evening out temperature. Under Mesophilic conditions a typical operating temperature is circa 38°C, with heat energy a significant input that can be greater in smaller farm scale based digesters with a higher surface area to volume ratio [27] but is greatly influenced by the initial feedstock temperature, ambient temperature and quality of insulation. Provision of this heat is by burning a proportion of biogas in a dedicated boiler or using a fraction of the heat from a Combined Heat and Power (CHP) unit. The eventual size of the CSTR reactor is dependent on the Organic Loading Rate that tends to be in the range of 1-4kgVS/m³/day [16] and Hydraulic Retention Time that depends on the rate of VS degradation. Typical CSTR retention times are around 25-35 days for animal manures whilst 60 to 90 days is common for fibrous energy crops.

1.3 Aims and Objectives

Dairy systems can vary, however all must face the reality that herd size in a pasture grazing system is limited by the amount of accessible grazing area. To enable herd expansion, cows are often housed for longer periods and fed alternative forages that as a consequence lead to a larger quantity of stored manure to be managed. The aim of this report is to investigate the individual gas sources and the mitigation potential of integrating anaerobic digestion into dairy farming, with specific reference to a commercial farm in Northern Ireland (NI). The principal objectives will be to quantify the GHG production of the case study farm; compare and contrast the environmental merits of this system with that of other widely used dairying systems; evaluate the impact of AD on the GHG sources and use the results gained to identify a route towards a 50% reduction of GHG for the case study farm.

2. Method and Materials for estimating emissions

To compare differences between dairy systems and take account of operational changes, such as the amount of time cows spend grazing or manure management policy changes, it was necessary to create a bespoke model to quantify the flow of CH_4 and N_2O gases on a monthly basis. Data from a 300 cow dairy unit; see Appendix 1, located in Armagh Northern Ireland (NI) between April 2019 to March 2020 is used to create the Reference Scenario (RS). By changing model parameters RS is compared with a more intensive Full Confinement (FC) and a less intensive Pasture Grazing (PG) scenario. The herd in the FC scenario is housed year round and fed silage; in RS they are at housed at night during the grazing season whilst the PG scenario assumes there is sufficient pasture close to the dairy unit for all day use during the grazing season.

2.1 Model development

The IPCC 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [28] was chosen to provide a detailed and internationally recognised methodology. With knowledge of feed intake and milk production the model goes beyond the basic Tier 1 characterisation and adopts a more comprehensive Tier 2 approach that the results from which could then be validated against the National Inventory reports of UK and Ireland.

For simplification it was assumed all lactations start and end on the first of the month and cows are at mature weight avoiding the need to estimate the energy requirement for growth of young cows. The impact of young stock and breeding heifers is also excluded as they are reared separately from the dairy unit.

2.2 Energy Requirement and forage provision

Quantifying Nett Energy (NE), MJ/cow/day requirements, to provide for Bodily Maintenance, Activity and Pregnancy that depend on animal weight and Milk Production that depends on yield and butterfat content is the starting point of the Tier 2 method. Mature cow weight was not known, but assumed to be 550kg aligning with data for NI dairy cows [29]. NE of grass and grass silage from work in Ireland [30] is taken as representative of farm produced forage, with Metabolisable Energy from bought-in concentrate converted to NE using the relationship defined by the National Research Council [31]. As cows are fed differing quantities of concentrate depending on milk yield and status, the model calculates a notional intake to arrive at a herd average NE from concentrate per cow per day.

During full time housing silage makes up the portion of NE not supplied from concentrate. In the grazing season, milking cows spend 1/3 of the day at pasture and are housed overnight fed on a mixed ration of silage and concentrate whilst dry cows graze all day. On this basis, the model creates a herd average Dry Matter Intake (DMI), kg/cow/day of silage and grass. To ensure best quality silage, only leafy first cut grass is used however for the purpose of modelling, the silage area will be adjusted to assume that a given area can produce all forage, see Appendix 2.

2.3 Modelling Methane emissions

Following the DMI estimation, the model calculates the Gross Energy (GE) of the ration using grass, silage and concentrate analysis figures obtained from research [29], [30] that allows calculation of Enteric CH_4 in kg, using IPCC derived Equation1, the Enteric Emission factor Y_m from IPCC tables and 55.65 that is the energy content of methane in MJ/kg CH_4.

$$Enteric\ CH_4 = \frac{GE \bullet (Y_m/100)}{55.65} \qquad \text{Equation 1}$$

Using figures for Digestibility (D) that is the percentage of GE converted to Digestible Energy (DE) of the feed and forage, allowed Equation 2 to calculate the excreted Volatile Solids (VS) as being the proportion of GE consumed that is indigestible. Under IPCC guidance, Urinary Energy (UE) is 0.04 for ruminant animals; Ash is the mineral fraction of the DMI obtained from feed analysis and 18.45 is the conversion factor for GE per kg of DM.

$$VS = \left[GE \bullet \left(1 - \frac{D}{100}\right) + (UE \bullet GE)\right] \bullet [(1 - Ash)/18.45] \qquad \text{Equation 2}$$

CH_4 emitted from Manure Management uses Equation 3 that employs the maximum CH_4 producing capacity of the manure (B_0, that is given to be 0.24 for European dairy cattle) and allows summation of results from each Agricultural Waste Management Systems (AWMS) employed using the Methane Conversion Factor (MCF) of each. Multiplying by 0.67 converts the result from m^3 CH_4 to kg CH_4.

$$Manure\ CH_4 = VS \bullet \left[B_0 \bullet 0.67 \bullet \left(\sum MCF/100 \bullet AWMS\right)\right] \qquad \text{Equation 3}$$

2.4 Modelling Nitrous Oxide emissions

Using the nitrogen content for feed and forage, less that retained for milk production allowed the excreted nitrogen flow into the manure management system (F_{MM}) to be estimated. The portion of F_{MM} lost from storage through direct N_2O and indirect Frac $_{GAS\_MM}$ (Gas Fraction, most initially lost as NH_3) is calculated using equation 4 that incorporates Emission Factor 3 (EF_3), the direct emission factor from manure management and Emission Factor 4 (EF_4), the emission factor

Equation 4

from surfaces provided for each AWMS from IPCC tables, with 44/28 the conversion for N_2 to N_2O based on atomic weights.

$$N_2O_{MM} = F_{MM} \bullet \left[EF_3 + \left(Frac_{GAS_{MM}} \bullet EF_4 \right) \right] \bullet \frac{44}{28}$$

N_2O from field deposited manure classified as Pasture, Range and Paddock (PRP) by the IPCC was calculated taking into account the proportions lost through volatisation at pasture (Frac $_{GAS\_PRP}$) and leaching/runoff (Frac $_{LEACH\_PRP}$) using Equation 5 and Emission Factor 5 (EF_5) the emission factor for nitrogen leaching and runoff.

$$N_2O_{PRP} = F_{PRP} \bullet \left[EF_3 + \left(Frac_{GAS_{PRP}} \bullet EF_4 \right) + \left(Frac_{LEACH_{PRP}} \bullet EF_5 \right) \right] \bullet \frac{44}{28} \qquad \text{Equation 5}$$

Using Equation 6, the annual N_2O emissions from Organic Animal Manure (AM) applications to managed soils were estimated based on the nitrogen F_{AM}, remaining after the losses in the manure management system; EF_1 the emissions factor from animal manure additions to managed soils; the volatisation Frac $_{GAS\text{-}AM}$ and Frac $_{LEACH\_AM}$ leaching/runoff fractions.

$$N_2O_{AM} = F_{AM} \bullet \left[EF_1 + \left(Frac_{GAS_{AM}} \bullet EF_4 \right) + \left(Frac_{LEACH_{AM}} \bullet EF_5 \right) \right] \bullet \frac{44}{28} \qquad \text{Equation 6}$$

Finally, the same could be done with equation 7 for the inorganic fertilisers (Synthetic Nitrogen, SN) applied to grazing and conservation areas with F_{SN} being the nitrogen added from fertiliser with specific EF_1 volatisation Frac $_{GAS\text{-}SN}$ and Frac $_{LEACH\_SN}$ related to the type of synthetic fertilisers used on the farm.

$$N_2O_{SN} = F_{SN} \bullet \left[EF_1 + \left(Frac_{GAS_{SN}} \bullet EF_4 \right) + \left(Frac_{LEACH_{SN}} \bullet EF_5 \right) \right] \bullet \frac{44}{28} \qquad \text{Equation 7}$$

With no land use change or significant changes to grass management during the year, it is assumed soil organic C is not lost, soil N is not mineralised to give rise to N_2O emissions and there are no drained organic soils on the farm that could give rise to N_2O emissions allowing the focus to be on the animals, the manure and emissions from grassland.

2.5 Modelling the Anaerobic Digester

The closed environment of the AD reactor reduces CH_4 and N_2O emissions. Using IPCC values, the reduced level of CH_4 emissions can be determined using Equation 3 with the MCF for AD instead of pit storage. Similarly, specific Frac $_{GAS\_AD}$ and EF_3 emission factors define N_2O emissions in Equation 4. As AD works best with a steady feed of VS, it was necessary to calculate the silage feedstock required to make up the shortfall with additional Nitrogen flow into the reactor from co-digested material added to the F_{MM} value and Equations 6 re-worked to establish the new N_2O emissions.

To determine the biogas production potential, a literature review will be conducted to draw together the published knowledge on the topic and predict the yield based on the VS content of the farm slurry and silage. Once complete, the factors will be loaded into the model that assumes the gas produced is used in a CHP engine, for which a typical thermal efficiency of 55% and electrical efficiency of 30% can be expected [32]. Heat consumption of 32kWh/tonne and electricity demand of 5.4kWh/tonne [18] is used to calculate the energy requirement of the AD systems.

By changing model parameters, the direct emissions effect of AD on RS can be compared with a FC and a PG scenario. CH_4 yields are calculated under each system and converted to units of Heat and Power to examine the potential savings of CO_2.

3. Case Study Farm (Reference Scenario) Results

The model highlights that Energy and Protein are key commodities. Energy quality and quantity defines emissions of C-gas (CH_4 and CO_2) whilst Protein content promotes N-gas emissions (N_2, NH_3 and N_2O). As expected, milk yield was the principal driver of energy requirement constituting

around 60% of the cows daily energy need, that peaks early in the lactation before tailing off. Quality of feed as defined by D value is equally significant as cows excrete the indigestible portion of GE as dung. Higher D value feeds such as fresh leafy grass (average D value 77%) result in less faecal energy loss and lower enteric emissions than silage (assumed D value 71%).

3.1 Methane emissions

In the chosen year the grazing season was approximately 3 weeks shorter than usual due to prevailing weather conditions, with cows turned out to grass on 19 April and housed full time from 16 October resulting in a housed period of 187 days. As total CH_4 emissions during the housing period are 392g/cow/day versus 353g/cow/day when cows are at pasture, each additional housing day raises daily emissions by 12%. Despite this issue, and the UK Inventory [33] being derived from a differing methodology there is only a 2.7% variance with UK national data, see Table 1, however the split between enteric and manure management origin is very different.

Table 1. Comparison of case study farm with Regional and National data

	IPCC 2006 default (West Europe)	IPCC 2019 default (West Europe)	Case Study Farm	Ireland National Inventory	UK National Inventory
Cow body weight (kg)	600	600	550	538	600
Milk Yield (kg/cow/yr)	6000	7410	7718	5300	8120
Digestibility of feed (%)	70	71	77	76	74.5
Enteric Methane (kg CH_4/yr)	117	126	128.26	115.21	122.71
Manure Management System	36% slurry, 37% solid, 20% pasture, 7% daily spread	43% slurry, 29% solid, 26% pasture, 2% daily spread	82% pit storage, 18% pasture	28% pit storage, 70% pasture, 2% deep bedding	61% slurry, 21% pasture, 9% solid, 8% daily spread
Manure Methane (kg/cow/yr)	21	not stated	35.88	10.36	37.26
Total Methane (kg/cow/yr)	138.00	not known	164.14	125.57	159.97
N excreted (kg/cow/day)	0.288	0.324	0.401	0.282	0.301

From Equation 1, GE and Emission Factor Y_m drive Enteric CH4 emissions with Y_m for medium producing European cows (5000-8500kg milk/yr) of 6.3 that is linked to a predicted D value of 63-70%, which is much less than the 77% achieved on farm indicating a lower Y_m might be appropriate. In confirmation, respiration studies [34] have indicated that Y_m for Danish cows could be 6.0 that if, applied to the farm would reduce emissions by 6kg CH_4/yr to align with UK Inventory data.

Considering efficiency of production, the lower input pasture grazing system of Ireland [35], fares worst at 21.73g CH_4/kg milk versus 16.64g CH_4/kg milk for the farm and 15.11g CH_4/kg milk for UK indicating that more intensive systems with greater levels of concentrate feed and less reliance on forage help reduce enteric CH_4 per unit of production.

On the farm 3 AWMS were in use (i) 6 month pit storage under confinement during winter, (ii) 3 month pit storage under confinement during grazing season and (iii) manure deposited on pasture during grazing season that had separate MCF's ranging from 21% for 6 months pit storage to 0.47% for manure deposited at pasture. Using Equation 3 and summing for the proportion of manure handled by each AWMS results in a cumulative 35.88 kg CH_4/cow/yr for the farm. The greater time at pasture has a profound effect, with Irelands CH_4 levels over 70% less than either the case study or UK farms.

3.2 Nitrous Oxide emissions

The IPCC approach to N_2O emissions is based on Nitrogen excretion, calculated from the Crude Protein intake of the diet less that retained for milk production or weight gain. As the model assumes cows to be at mature weight, nitrogen retention is only for milk production and consequently may be lower than reality. The farm results are higher than other values in Table 1, however when excreted nitrogen is expressed per unit of milk production the farm becomes 18.96g/litre that is comparable to the 19.40g/litre reported by Ireland. As excreted nitrogen is highly dependent on diet [36] cows fed a lower crude protein concentrate or maize silage that has low protein content will make more efficient use of this input and could go some way to explaining the 13.5g/litre figure reported by UK.

Direct N_2O losses from manure storage are low due to lack of oxygen in the anaerobic environment of pit storage with IPCC indication that 0.2% of manure N is lost through this route. Indirect emissions account for a more significant nitrogen loss with 28% as NH_3 and NO_x gases and a further 0.6% as N_2 gas. In a wet climate, that is typical of UK and Ireland, 14% of these indirect emissions are deemed to convert to N_2O that constitutes a combined 0.34 tonne N_2O per year from pit storage.

In contrast to the CH_4 analysis, there was no disaggregation factor for length of storage and so these loss fractions can only be applied on an annual basis. Carrying forward the 28.8% loss from pit storage, the remaining N content of the manure is subject to further loss during field application that can vary depending on season of application, weather conditions and application method [37] but to avoid complication the IPCC loss of 45% applied nitrogen has been used that is composed of 21% from volatisation during spreading and 24% from leaching and runoff. N_2O emissions factors in a wet climate from this nitrogen loss are 0.6% from manure N (EF$_1$), 1.4% from volatisation N (EF$_4$) and 1.1% for leaching/runoff (EF$_5$) with the calculated N_2O emissions of 0.44 tonne per year using Equation 6. In parallel manure deposited on pasture by grazing cows emits N_2O at the same N loss rates, EF$_4$, and EF$_5$ as for manure spreading with EF$_3$ for cattle manure in a wet climate of 0.6% which is calculated to be 80kg/yr using Equation 5.

In a significant change from the IPCC 2006 method that assumed a 1% loss of N from all inorganic fertiliser, the IPCC 2019 Refinement enables the volatisation of inorganic fertilisers to be split by origin that range from 1% N loss for Nitrate based through to 15% for Urea whilst the compound fertilisers used on the farm are from an Ammonium Nitrate base that has a volatisation fraction of 5% N applied. With EF$_1$ for synthetic fertilisers of 1.6% and the same soil leaching/runoff fraction, EF$_4$ and EF$_5$ values as for organic manures Equation 7 estimates that 30.4g N_2O are released for every kg of N applied. In total, 17.84t of N is applied as inorganic fertiliser across the grass area that emits 542kg of N_2O gas. Across the herd, this makes total N_2O emissions of 1.44 tonne/yr or 4.85kg N_2O/cow/yr.

4. Slurry and Silage Results

Many factors affect the composition of slurry with diet, feeding system, volume of dirty water, rainwater and any bedding materials contributing to the variance. For the purpose of estimating storage needs in the UK, the quantity of undiluted excreta for a medium-producing (6000-9000 litre) cow is considered to be 53kg per day [38], rising to 64kg per day for higher yielding cows. Dry solid content of slurry can vary from 2-10%, with 6% [39] considered typical for the UK, whilst in AD studies, total solids have been measured at 8.75% [40] in Ireland and 6.9% [18] in Northern Ireland when manure is captured by similar systems as the case study farm. An average figure of 7.2% has been used for calculations. Crop available nitrogen in the form of NH_4NO_3 is indicated to be 35% of total nitrogen in raw slurry [39].

On the farm, slurry quantities are not measured however with no outside collecting yards to introduce rainwater contamination and milk washings handled separately, the only additions will be dirty water from washing down equipment assumed to be 10% and spillages from drinking water assumed to be 5% of excreted manure. Bedding materials of circa 200kg per day sawdust across the herd supplement the rubber matted cubicle area contributing to manure solids that are assumed to be inert. Based on an assumed 61.7kg of slurry addition to storage per cow per day during the full

time housing period when average VS was 4.3kg/cow/day indicates a VS content of 69.8g/kg slurry that compares to 66.9g/kg slurry for Irish cows [40] and Danish cows at 72.3g/kg slurry [11]. During the grazing season when VS content is lower due to the higher digestibility of fresh grass, the value drops to return an average of 66.4g/kg collected in storage over the year. Whilst dilution could play a part in the variance, it is more likely to be driven by diet, as Irish cows are fed lower levels of concentrate and rely more on fresh grass compared to Danish cows that are often housed year round with a higher reliance on concentrate and silage.

A theoretical prediction of gas yield based on the stoichiometric analysis of the VS fractions of slurry are possible using the Buswell equation however the result is based on the assumption that all VS are fully degraded. The reality is often much less and better reflected in a laboratory assessed Biomethane Potential (BMP) of the feedstock. Research in Ireland [40] has found that the Buswell prediction for cow slurry was 389 L CH_4/kg VS whilst the measured BMP was 239 L CH_4/kg VS and the Buswell prediction for grass silage was 443 L CH_4/kg VS with a measured value of 400 L CH_4/kg VS and a VS content of 91.7% Total Solids. In separate work [41], two batches of cattle slurry were assessed to have a BMP of 246 and 269 L CH_4/kg VS. The BMP of Grass Silage can also vary depending on grass variety, stage of maturity, success of preservation and measurement accuracy, with a BMP of 359 and 428 recorded for two separate ryegrass silages [41] and 350 and 493 for the same silage sample under differing measurement techniques [42] that subsequently achieved a yield of 451 L CH_4/kg VS from mono-digestion of grass silage in a two stage CSTR reactor over a 50 day period. Co-digesting of cattle slurry and grass silage was observed [40], [41] to have the antagonistic effect of reducing predicted BMP by an average 7% that was most pronounced at a 50:50 mix below mono digestion of each substrate.

Averaging the BMP assumptions, see Appendix 3 would indicate that the farm slurry can produce 16.7 L of CH_4 per kg that is 9% above the 15.2 L CH_4 / kg slurry achieved from 2 years AD operation [18] indicating that laboratory figures are difficult to achieve in practice. Assuming farm silage has 24% DM, that is common for pit silage and 91.7% of total solids are volatile, the VS content is 220g/kg and using average BMP figures, Appendix 3, indicates fresh silage can produce 91 L CH_4 per kg, 5.5 times more than from cow slurry. Allowing for the differences in DM, this ratio is directly equivalent to the 6.7 fold increase [40] recorded with 29% DM silage.

5. Results and Discussion of systems modelling before and after AD

5.1 Systems comparison before AD

As expected from the literature, Enteric Methane dominates at between 71-81% of CH_4 emissions depending on farming system employed, see Table 2 and is lowest in the PG (Pasture Grazing) system that relies most heavily on high digestibility fresh grass. Manure storage CH_4 emissions are lowest under the PG (Pasture Grazing) system where 80% of manure is deposited at pasture during the grazing season and only 4114t of slurry is collected during the year. By comparison, the FC (Full Confinement) regime collects all 6712t of slurry produced during the year and produces significantly more from manure management. N_2O emissions from manure storage and field application follow a similar pattern, however the PG system has higher N_2O emissions resulting from the greater amount of pasture deposited manure and increased proportion of grazing land that has higher inorganic fertiliser use with a consequent higher N_2O emissions. The effect of pollution swapping is clearly visible when comparing the N_2O emissions that are highest for the PG system, which had the lowest CH_4, however when related back to CO_2 eq by using their GWP_{100} values the FC system has the most polluting effect.

Table 2, Dairy herd GHG emissions by source under differing herd and manure management systems

	RS	RS with AD	FC	FC with AD	PG	PG with AD
Enteric CH_4 (kg/yr)	38135	38135	39417	39417	37036	37036
Manure Storage CH_4 (kg/yr)	10692	653	16019	763	8751	549
Total CH_4 emissions (kg/yr)	**48827**	**38788**	**55436**	**40180**	**45787**	**37585**
Manure Storage N_2O kg/yr	344	84	403	91	257	136
Manure Field Losses (Spreading, Leaching, Runoff) N_2O (kg/yr)	479	708	561	771	357	1150
Pasture Losses N_2O (kg /yr)	80	80	0	0	191	191
Inorganic Fertiliser N_2O (kg/yr)	542	537	348	293	666	704
Total N_2O (kg/yr)	**1444**	**1408**	**1311**	**1155**	**1471**	**2181**
Adjusted land area required (ha)	90	104	88	93	90	113
CO_2 eq (tonne/yr)	**1750**	**1459**	**1900**	**1431**	**1672**	**1630**

5.2 Systems comparison after AD

The closed environment of the digester enables creation and capture of all volatised gas however a percentage will always be lost primarily from operations occurring before manure is loaded into the reactor. CH_4 loss is estimated by MCF from IPCC tables [28] that range from 1% for a high quality digester with gas tight storage to 3.55% for a high quality digester with open digestate storage in a cool climate. Data from the model in Table 2 is calculated assuming the digestate is stored in a gas tight environment. IPCC methodology also suggests that N loss in Manure Management is reduced from 28% to 5% and assuming crop available N is increased by 20% [18] from the 35% in raw slurry [39] there is a significant nutrient benefit. Although higher N content digestate increases the losses from land spreading and soil emissions, the model assumes that inorganic N application across the silage area can be reduced by 20%.

In RS (Reference Scenario), the model calculated that 5630t of slurry is added to storage during the period under consideration. VS production by the herd varies from 43.5t in March 2020 when the majority of cows are at peak production to 31.8t in September 2019 that coincides with the lowest number of lactating cows with the low point further reduced to 21.2t collected into storage due to 1/3 of manure being deposited at pasture. As AD operation is most stable with a continuous feedstock supply raising VS shortfall across the year to the peak of 4.84kg/cow/day seen in March would require the addition of 154t VS from grass silage that corresponds to 699t fresh silage (24% DM). It is estimated that the required grass silage could be harvested from an additional 14ha of adjusted silage area.

Under FC scenario cow numbers and milk yield create the only variation of VS additions to storage with the model calculating that to maintain the target 4.84kg/cow/day for the 298 cow herd there is a shortfall of 53t VS, requiring 243t of fresh silage. In the PG scenario where cows graze all day between turnout on 19 April until winter housing on 16 October without any silage feed, 1164t fresh silage from an additional adjusted silage area of 24ha is required.

5.3 Discussion

Whilst AD can reduce CH_4 emissions by 18-28% depending on farm system, gas tight storage is essential as fugitive emissions of only 3.6% can wipe out any advantage due to the GWP_{100} of this gas. By comparison AD can limit the N_2O emissions from manure storage by 47-77% but these gains are not permanent and can be eroded by higher field emissions related to spreading technique or timing that cannot be explored by current IPCC methodology. However, despite field losses, the higher available N from digestate enables lower inorganic fertiliser use per hectare. In the case of the PG with AD scenario, the very much higher volume of digestate spread to land trebles N_2O emissions from field losses and increases the N_2O from inorganic N applications to the additional silage area

grown as an energy crop virtually wiping out any gain from the captured CH_4. From an environmental perspective, introducing AD to a Pasture Grazed system should therefore only be contemplated if a strategy for controlling N_2O emissions can be put in place.

Setting aside enteric production, that is best tackled by diet manipulation [36], it is therefore obvious that for slurry-based systems, CH_4 emissions are greatest during manure storage, NH_3 emissions are greatest from animal confinements and most N_2O losses occur in the field. Consequently, successful mitigation options for CH_4 must target the manure collection and storage systems, NH_3 mitigation must focus on building usage and design whilst the priority to reduce N_2O emissions has to be more efficient fertiliser and manure application to land. Emissions mitigation can take many forms, but care needs to be exercised to avoid unintentional pollution swapping. For example, if CH_4 is reduced by increasing the time cattle spend grazing on pasture; pollution swapping occurs with more N_2O produced as manures degrades aerobically in the field but indirect emissions of N_2O will decrease because animals spend less time in housing where NH_3 is emitted from manures.

Compared to the RS farm situation of today, introducing AD would reduce GHG emissions by 16.6% with the best outcome of 24% reduction from the year round housed FC scenario, however if CO_2 emissions from silage machinery operations are taken into account, much of this advantage will be lost due to the larger volume of silage required to feed the herd year round in the FC system. The PG grazing herd sees the least benefit as emissions from a big increase in silage area consumes almost all gains from AD. In addition, farm based AD is preferable to larger industrial reactors as manures are processed on site shortly after production with minimal loss of gas potential and no fossil fuel CO_2 penalty for transporting slurry to a central plant and returning the digestate to the farm. In all instances, if land area is constrained, each additional hectare of energy crop silage required to feed the reactor would require the herd size to reduce by 3.3 cows, impacting on the revenue from milk sales.

6. Creating Value from BIOGAS

6.1 Environmental considerations

As the CO_2 component of biogas is from a biogenic source that as yet has no commercial value, the impact of this portion of the biogas has been ignored. Focussing on the CH_4 each scenario delivers a differing yield, depending on the amount of manure captured and the fraction of VS provided by grass silage. The highest gas yield occurs with the PG scenario that has the largest addition of grass silage during the grazing season, whilst the FC scenario where the requirement for additional silage is small, has the lowest yield, see Table 3.

At a higher heating value of $37.8MJ/m^3$ [16] the energy potential in the captured gas is significant and could be directly realised if injected into the gas grid. For small-scale farm based digesters, the cost and complexity of this route is often prohibitive with the result that most are configured with a CHP engine. After providing for the heating, pumping and stirring needs of the reactor, the CHP produces both Thermal and Electrical Energy, with the nett figures available for use. The electricity produced is more than the annual 90MWh requirement of the farm to power the milking machines, cool milk, run the automatic yardscrapers and provide lighting. The dairy has little demand for Heat aside from water heating, but with additional infrastructure a more significant proportion of the heat could be used in the farm dwellings to replace the current kerosene fuelled central heating systems. In a situation where all of the heat and power generated could be put to productive use, installing an AD system on the farm would potentially save 715t CO_2 per year, see Table 3, that is a 41% saving compared to the situation of today. AD has a positive environmental benefit on the 3 farming systems examined with GHG savings of between 32-44% CO_2 eq achieved. Reductions are greatest for Full Confinement (FC) herds with the most manure stored under anaerobic conditions and least for herds that are Pasture Grazed (PG) on high quality fresh grass that excrete up to 80% of manures on pasture during the grazing season.

To achieve an objective of 50% reduction, other opportunities need to be explored. Instead to release the CO_2 that makes up approximately 45% of biogas back to atmosphere, this gas could be exploited to promote plant growth in glasshouses or to displace fossil fuel CO_2 in another industrial process. Alternatively as the CO_2 is captive, there might at some future point be a Carbon Capture and Storage scheme.

Improving the efficiency of CH_4 usage could also bring advantage. As the CHP operates at a combined efficiency of 85% [32] to produce power and heat beyond the farm needs, diverting a percentage of CH_4 for use in tractors, road going vehicles and other machines to tackle the 40,000 litres of diesel consumed annually on the farm and potentially avoid the 110t CO_2 impact (at 2.75821 kg of CO_2 eq per litre [44]) would bring immediate benefit. However, whilst methane powered tractors are nearing commercialisation, there is an obvious need for small scale CH_4 purification plant to make a farm based system achievable.

Table 3. Energy yield and CO_2 saving from CH_4 portion of biogas

	RS with AD	FC with AD	PG with AD
CH_4 yield (m^3)	157544	141173	174211
Gross Energy (MWh)	1654	1482	1829
Nett Thermal Energy (MWh)	707	593	837
Nett Electrical Energy (MWh)	462	407	520
CO_2 saving from emission reduction (tonne/yr)	**291**	**469**	**42**
CO_2 saving from HEAT* (tonne/yr)	**193**	**162**	**229**
CO_2 saving from electricity (tonne/yr)	**231**	**203**	**259**
TOTAL CO_2 saving tonne/yr	**715 (41%)**	**834 (44%)**	**530 (32%)**

* Basing CO2 savings of 0.27315kg CO_2 eq / kWh for heat generated from oil fired central heating [44]; ** Basing CO_2 savings on the Carbon Intensity of generation from Natural Gas at 499kg CO_2 eq/ MWh [45]

6.2 Financial considerations

As each AD system is a bespoke design, build costs can vary immensely. Factors affecting capital cost include specific civil works on site, reactor design that is dependent on feedstock characteristics and residence time, together with electricity or gas grid connection and plant needed to purify or convert the gas to usable power. Storage for energy crops can also add to the burden, that taking the example of the current farm would need an additional 700t on top of the existing capacity for 3139t. Consequently this study did not attempt to estimate these costs but examine potential sources of revenue.

In so far as the author is aware, there is no direct financial reward for pollution reduction from manures in agriculture, therefore to be financially viable the revenue from electricity and heat must be sufficient to cover the capital, operational and maintenance costs. Consuming the heat and power on site brings greater benefit than exporting to the grid as displacing electricity bought either at the daytime rate of 16.55p/kWh or evening rate of 7.47p/kWh is more favourable than exporting to the grid at a Feed In Tariff (FiT) of 4.6p/kWh. With approximately 2/3 of electricity bought at the daytime rate and power not consumed on site exported, the farm savings and earnings from grid exportation amount to £29,191 per year. Savings from heating the 3 dwelling houses amount to a further £2700 of avoided kerosene cost making total potential revenue of £31,891 that although significant is unlikely to justify the investment. Regional or national government support could be instrumental in overcoming this hurdle either using capital grants targeted towards the pollution reduction potential of systems or tax breaks to encourage investment. Ongoing enhanced payments could also be used to demonstrate a revenue stream to support bank borrowing but FiT based systems, unless linked to a carbon reduction incentive, can encourage owners to maximise subsidy payments.

The value of electricity could be increased by a factor of 3 or more if sold direct to a third party through a Power Purchase Agreement (PPA) or to the systems operator for frequency support at times of peak demand. Heat that is an underused resource within the current operation could be

exploited by an alternative enterprise either on- or off-farm to generate an income rather than simply exhausted to atmosphere. Alternatively feeding the grass silage, that has a 5.5 times greater CH_4 yield per ton than cow slurry, direct to the reactor could substantially increase the FiT or PPA revenue, but this would come at the expense of reducing the size of the dairy herd.

Setting aside the concentrate and grass inputs, each cow in the current system consumes 10.5t of silage per year to excrete 18.9t slurry into storage that has the potential to generate 287m^3 of CH_4, whereas if the same 10.5t silage was fed direct to the digester 956m^3 of CH_4 could be produced. Further analysis is required to determine under which circumstances this additional 669m^3 of CH_4 could be more valuable than the 7.7t of milk each cow produces in the year.

7. Conclusion

This study has determined annual GHG emissions from a 298 cow dairy unit in Northern Ireland to be 1750t CO_2 eq made up of 48.8t CH_4 and 1.4t N_2O, with manure management and field loss responsible for 30.8% of this total. GHG levels are highest as milk production increases with CH_4 levels per litre of milk linked to feed quality and manure storage, whilst N_2O emissions depend most on dietary protein content and field N losses.

By modelling alternative farm systems, AD is confirmed as an ideal pollution control achieving savings of 32-44% CO_2eq, with the best improvement for Full Confinement herds. Exploiting the CO_2 component of biogas and the ability to use CH_4 to power farm vehicles are seen as routes to achieve an objective of 50% reduction, but will require technology advances before to become an affordable reality.

Despite substantial GHG reduction potential, this study has concluded farm-scale AD is not financially viable in the current climate. Capital grants and tax breaks could help overcome high establishment costs whilst funding directed towards pollution control could favour manure based feedstocks instead of energy crops enabling AD to make greater contributions towards the 2050 GHG reduction commitments of national governments.

Author Contributions: Conceptualization AS, RB; methodology AS, RB; validation AS, RB; formal analysis AS; investigation resources AS; data curation AS; writing-original draft preparation AS; writing review and editing RB, AS; supervision RB; project administration RB, AS. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix 1. Farm description

The case study is of a 300-cow dairy unit located in Armagh, Northern Ireland (NI) over a 12-month period from April 2019 to March 2020. The herd follows a year-round calving pattern, with a 305-day lactation and 2 month dry period prior to calving. Cows are milked twice per day in a rotary parlour and housed in open stall cubicles with pit storage under slatted floors that has 6 months of manure storage capacity. Lactating cows receive a grain-based concentrate feed during milking linked to yield and a lesser amount mixed with the evening silage feed. Dry cows are held separately and fed a lower energy concentrate.

From mid-November to mid-April all cows are housed on a full-time basis and fed silage in addition to the bought-in concentrate. However, during the grazing season milking cows graze pasture between morning and evening milking that is estimated to be 1/3 of the day and are housed overnight with a ration of 5kg silage per cow on a Dry Matter (DM) basis mixed with additional concentrate, whilst dry cows graze day and night.

The grazing area received 7 applications of 27% Calcium Ammonium Nitrate (CAN) following the rotational grazing pattern of the herd to deliver 350 kg N/ha/yr across the 28ha of land allocated to grazing. In addition, there are 130ha that receive spring slurry and 63kgN/ha to provide the first cut silage for the dairy herd. Subsequent fertilising and grass harvesting from this silage area provide for the beef enterprise that is outside the scope of this study.

Cow records provide data on herd size and calving date with milk yield provided from processing plant records, concentrate delivery data is taken to be indicative of consumption rates and available silage sample records assumed to be representative of all ensiled grass.

Appendix 2. Grass and Silage production

Using data from Recommended Lists [43] the 242t DM grass requirement of the herd could be met from 24.5ha grazing area assuming a grazing yield of 9.87t DM/ha and the 753t DM silage requirement could be met by 103ha at a first cut conservation yield of 7.34 t DM / ha. However, replicating field trial performance at farm scale across varying soil types, field aspects, and differing grass varieties will always create discrepancy. In reality the grazing area is calculated to provide 8.64tDM/ha (88% of potential) and the silage area yield is 5.79tDM/ha (79% of potential). For the purpose of modelling, the silage area will be adjusted to assume that a given area can produce all the forage at a 79% factor of the potential annual yield of 15.35tDM/ha. Under the baseline scenario this assumption would produce 12.13tDM/ha and require 4 cuts from 62ha land area.

Appendix 3. Anaerobic Digester input assumptions

Slurry characteristics Kg/cow/day		AD feedstock characteristics	
Manure excretions	53	BMP slurry	251 litres CH_4/kg VS
Water additions	8	Average VS content of slurry	66.4g/kg
Sawdust bedding	0.7	BMP grass silage	414 litres CH_4/kg VS
Slurry volume	61.7	VS content of silage	220g/kg

References

1. United Nations Framework Convention on Climate Change (UNFCCC). Paris Agreement. December 2015
2. UNEP 2011. Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers. United Nations Environment Programme (UNEP), Nairobi, Kenya, 78pp.
3. G. Myhre, D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura , H. Zhang.   Anthropogenic and Natural Radiative Forcing. [T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (Eds.)]. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
4. P.J. Gerber, H. Steinfeld, B. Henderson, A. Mottet, C. Opio, J. Dijkman, A. Falcucci, G. Tempio, 2013. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome.
5. G.J. Monteny, C.M. Groenestein, M.A. Hilhorst.   Interaction and coupling between emissions of methane and nitrous oxide from animal husbandry. Nutrient Cycling in agroecosystems, 2001, Volume 60 (1), Pages 123-132.
6. L. Brown, B. Syed, S.C. Jarvis, R.W. Sneath, V.R. Phillips, K.W.T. Goulding, C. Li.   A Development and application of a mechanistic model to estimate the emission of nitrous oxide from UK agriculture. Atmospheric Environment, Volume 36, Issue 6, 2002, Pages 917 - 928.
7. O. Oenema, D. Oudendag, G.L. Velthof.   Nutrient losses from manure management in the European Union. Livestock Science, Volume 112, Issue 3, December 2007, Pages 261-272.
8. D. Chadwick, S. Sommer, R. Thorman, D. Fangueiro, L. Cardenas, B. Amon, T. Misselbrook. Manure Management: Implications for greenhouse gas emissions. Animal Feed Science and Technology, Volumes 166-167, June 2011, Pages 514-531.
9. W. Burchill, F. Reville, T.H. Misselbrook, C. O'Connell, G.J. Lanigan. Ammonia emissions and mitigation from a concrete yard used by cattle. Biosystems Engineering, Volume 184, August 2019, Pages 181-189

10. E.P.M. Sajeev, W. Winiwarter, B. Amon. Greenhouse gas and ammonia emissions from different stages of liquid manure management chains: Abatement options and emission interactions. Journal of Environmental Quality, December 2017

11. S.G. Sommer, S.O. Petersen, P. Sorensen, H.D. Poulsen, H.B. Moller. Methane and carbon dioxide emissions and nitrogen turnover during liquid manure storage. Nutrient Cycling in Agroecosystems. Volume 78, Issue 1, May 2007, Pages 27-36.

12. S.G. Sommer, S.O. Petersen, H.B. Moller. Algorithms for calculating methane and nitrous oxide emissions from manure management. Nutrient Cycling in Agroecosystems Volume 69, Issue 2, June 2004, Pages 143-154.

13. T.H. Misselbrook, K.A. Smith, R.A. Johnson, B.F. Pain. Slurry application techniques to reduce Ammonia emissions: Results of some UK field-scale experiments. Biosystems Engineering, Volume 81,Issue 3,March 2002,Pages 313-321.

14. I.K. Thomsen, A.R. Pedersen, T. Nyord, S.O. Petersen. Effects of slurry pre-treatment and application technique on short-term N2O emissions as determined by a new non-linear approach. Agriculture, Ecosystems & Environment, Volume 136, Issues 3-4, 15 March 2010, Pages 227-235.

15. J. Clemens, M. Trimborn, P. Weiland, B. Amon. Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. Agriculture, Ecosystems & Environment, Volume 112, Issues 2-3, February 2006, Pages 171-177.

16. J.D. Murphy, T.Thamsirioj. Chapter 5 - Fundamental science and engineering of the anaerobic digestion process for biogas production. The Biogas Handbook, Science Production and applications, Woodhead Publications series in Energy, 2013, pages 104-130.

17. P. Weiland. Biomass Digestion in Agriculture: A successful pathway for the energy production and waste treatment in Germany. Engineering in Life Sciences, June 2006

18. P. Frost, S. Gilkinson. Interim Technical report – 27 Month performance summary for Anaerobic Digestion of diary cow slurry at AFBI Hillsborough, March 2010

19. I. Pérez Domínguez, T. Fellmann, P. Witzke, F. Weiss, J. Hristov, M. Himics, J. Barreiro-Hurle, M. Gómez Barbero, A. Leip. Economic assessment of GHG mitigation policy options for EU agriculture: A closer look at mitigation options and regional mitigation costs (EcAMPA 3). EUR 30164 EN, Publications Office of the European Union, Luxembourg, April 2020, ISBN 978-92-76-17854-5, doi:10.2760/4668, JRC120355

20. L.Hoglund-Isaksson, W. Winiwarter, P. Purohit, A. Gomez-Sanabria. Non-CO2 greenhouse gas emissions in the EU-28 from 2005 to 2050: Final GAINS Reference scenario 2016. GAINS model methodology. IIASA Report. International Institute for Applied Systems Analysis, Laxenburg, Austria.

21. A. Van den Pol-van Dasselaar, D. Hennessy, J. Isselstein. Grazing of dairy cows in Europe: an in-depth analysis based on the perception of grassland experts. Sustainability, Volume 12, Issue 3, February 2020, Article 1098

22. D. Cappolecchia, D. Gardoni, C. Baldini, F. Borgonovo, M. Guarino. The influence on biogas production of three slurry handling systems in dairy farms. Journal of Agricultural Engineering,Volume 46,Number 1,Pages 30-35, April 2015

23. T.L.I. Vergote, W.J.C. Vanrolleghem, C. Van der Heyden, A.E.J. De Dobbelaere, J. Buysse, E. Meers, E.I.P. Volcke. Model-based analysis of greenhouse gas emission reduction potential through farm-scale digestion. Biosystems Engineering, Volume 181, May 2019, Pages 157-172.

24. H. Himanshu, J.D. Murphy, J.J. Lenehan, P. O'Kiely. Impacts of characteristics of grass silage and cattle slurry feedstocks on the cost of methane production. Biofuels Bioproducts and Biorefining, Volume 13, Issue 1, January/February 2019, Pages 129-139.

25. H. Baldé, A.C. VanderZaag, S.D. Burtt, C. Wagner-Riddle, A. Crolla, R.L. Desjardins, D.J. MacDonald. Methane emissions from digestate at an agricultural biogas plant. Bioresource Technology, Volume 216, September 2016, Pages 914-922.

26. L.K.K. Rodhe, J.Ascue, A.Willen, B.V. Persson, A. Nordberg. Greenhouse gas emissions from storage and field application of anaerobically digested and non-digested cattle slurry. Agriculture, Ecosystems & Environment, Volume 199, January 2015, Pages 358-368.

27. C. Lukehurst, A. Bywater. Exploring the viability of small-scale anaerobic digesters in livestock farming. IEA Bioenergy 2015

28. Intergovernmental Panel on Climate Change (IPCC) - IPCC 2019, Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories, accessed 12 June 2020

29. D.N. Hynes, S. Stergiadis, A. Gordon, T. Yan. Effects of crude protein level in concentrate supplements on animal performance and nitrogen utilisation of lactating dairy cows fed fresh cut perennial grass. Journal of Dairy Science, Volume 99, Issue 10, Pages 8111-8120.

30. F.P. O'Mara. Climate Change – Development of emission factors for the Irish Cattle Herd, Special Report. Environmental Protection Agency 2006.

31. National Research Council. NRC (2001) Nutrient Requirements of Dairy Cattle: Seventh Revised Edition, 2001. Washington DC: The National Academies Press, Page 13.

32. S.O'Connor, E. Ehimen, S.C. Pillai, G. Lyons, J. Bartlett. Economic and Environmental analysis of Small-Scale Anaerobic Digestion plants on Irish dairy farms. Energies, February 2020, Volume 13, Issue 3, Article 637.

33. B. Richmond, A. Misra, M. Broomfield, P. Brown, E Karagianni, T. Murrells, Y. Pang, N. Passant, B. Pearson, R. Stewart, G. Thistlethwaite, D. Wakeling, C. Walker, J. Wiltshire, M. Hobson, M. Gibbs, T. Misselbrook, U. Dragosits, S. Tomlinson. UK informative inventory report (1990-2017). DEFRA published April 2019

34. A.L.F. Hellwig, M.R. Weisbjerg, M. Brask, L. Astrup, M. Johansen, L.Hymøller, M.K. Larsen, P.Lund. Prediction of the methane conversion factor (Y_m) for diary cows on the basis of national farm data. Animal Production Science, Volume 56, Issue 3, Pages 535-540, February 2016.

35. P. Duffy, B. Hyde, A.M. Ryan, J. Murphy, B. Quirke, D. Fahey. Ireland informative inventory report 2019. Environment Protection Agency.

36. T. Misselbrook, A. del Prado, D. Chadwick. Opportunities for reducing environmental emissions from forage based dairy farms. Agriculture and Food Science, Volume 22, Issue 1, Pages 93-107, March 2013.

37. R.E. Thorman, F.A. Nicholson, C.F.E. Topp, M.J. Bell, L.M. Cardenas, D.R. Chadwick, J.M. Cloy, T.H. Misselbrook, R.M. Rees, C.J. Watson, J.R. Williams. Towards Country-specific Nitrous Oxide emission factors for manures applied to arable and grassland soils in the UK. Frontiers in Sustainable Food Systems.

38. Agriculture and Horticulture Development Board (AHDB), Slurry www.ahdb.org.uk/knowledge-library/slurry-wizard, accessed 24 July 2020.

39. Agriculture and Horticulture Development Board. AHDB Nutrient Management Guide (RB209), February 2020 edition.   https://ahdb.org.uk/RB209 , accessed 11 August 2020.

40. D.M. Wall, P. O'Kiely, J.D. Murphy. The potential for biomethane from grass and slurry to satisfy renewable energy targets. Bioresource Technology, Volume 149, Pages 425-431. December 2013.

41. H. Himanshu, J.D. Murphy, J. Grant, P. O'Kiely. Antagonistic effects on biogas and methane output when co-digesting cattle and pig slurries with grass silage in in-vitro batch anaerobic digestion. Biomass and Bioenergy, Volume 109, February 2018, Pages 109-198.

42. A.S. Nizami, A. Orozco, E. Groom, B. Dieterich, J.D. Murphy. How much gas can we get from grass ? Applied Energy, Volume 92, April 2012, Pages 783-790.

43. British Grassland Society. Recommended Grass and Clover lists for England & Wales 2020/21

44. Department for Business, Energy and Industrial Strategy – UK Government. Greenhouse Gas Reporting: conversion factors 2020. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020, accessed 30 August 2020.

45. Gridwatch.co.uk - GB Electricity National Grid CO_2e Output per production type. https://gridwatch.co.uk/co2-emissions, accessed 30 August 2020.