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Evaluating the opportunity for utilising anaerobic digestion and pyrolysis of livestock manure and grass silage to decarbonise gas infrastructure: A Northern Ireland case study

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ABSTRACT

The need to mitigate climate change and improve energy security has led to an increasing interest in the utilisation of renewable gas to decarbonise natural gas use. Northern Ireland serves as an interesting case study to evaluate how biomethane from manure and silage material can displace natural gas. This is because of high agricultural intensity, the low penetration of gas relative to the wider UK and the modern pipeline infrastructure. This study included spatial mapping of biomethane yield and life cycle assessment for processing scenarios. The results demonstrated that current manure management i.e., storage and application of manure to grassland, results in 344 kg CO_2 equivalent/person of greenhouse gases and 9.7 kg/person of ammonia being emitted. In a second scenario where collected manure and underutilised grass silage is routed to anaerobic digestion, the estimated net energy produced is 6124 GWh, with −464 kg CO_2 equivalent/person. A third scenario, combining anaerobic digestion and pyrolysis, also produces 6124 GWh and 200 kilo tonnes of biochar (retaining 64% of manure phosphorus), −563 kg CO_2 equivalent/person. This research evaluates the opportunity for biomethane while acknowledging that a comprehensive approach which balances energy potentials and nutrient management is required for sustainable biomethane based decarbonisation.

1. Introduction

1.1. Background

The Paris Agreement has committed countries to regulate greenhouse gas (GHG) emissions to limit the increase in global average temperature to below 2 °C above pre-industrial levels, and to invest in pathways that support low GHG emissions. In the United Kingdom (UK) the amendment to the Climate Change Act 2008 [1] sets a net zero ambition, committing the UK to a 100% net reduction in GHG emissions by 2050 compared to 1990 levels. While emissions from the electricity sector have fallen significantly, there has been much less progress in the natural gas sector [2].

There are many opportunities to realise a decarbonised gas grid, including green-hydrogen and blue-hydrogen with additional carbon mitigation (noting that carbon capture and underground storage is not 100% effective). Within agriculturally rich regions such as Northern Ireland, biogas (methane ~55% and CO_2 ~45% in composition) can play a significant role in grid decarbonisation, as the biomethane produced from anaerobic digestion (AD) using organic sources such as livestock manure and grass silage can provide an alternative energy source [3–7], and therefore, a potential solution to the much-needed energy transition. Biomethane can be used as a bioenergy source for heating, transport and a variety of industrial purposes in the same way as natural gas, with no major changes needed to the already existing gas grid infrastructure or appliances at the point of consumption, such as boilers. In addition to the production of biomethane, the rerouting of manure from farms to AD facilities offers opportunities for increased control and circularity of farm nutrients such as phosphorus (P) and nitrogen (N). This is in line with a circular economy approach; i.e. eliminate waste and pollution, circulate materials and products,

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and regenerate nature.

1.2. Relevant literature and knowledge gaps

To assess the feasibility of a decarbonised gas grid, an important key step is a proper assessment of biomethane potential. The availability of agricultural residue feedstock for AD is an important component of this assessment and is region specific, depending on variables such as climate, soil characteristics, policy and agricultural practices. Geographical Information Systems (GIS) have been used in a number of studies to evaluate biomethane potential on a regional basis, such as in Ireland [8]; in Europe [9,10]; and in Greece and China [11,12]. To date, there is no study that presented feedstock quantities and biomethane yield maps collocated with natural gas demands in Northern Ireland.

As of today, controlled biomethane generation from biomass is a mature technology. However, the environmental impact of the process depends largely on the existing regional agricultural practices such as manure and grass silage management characteristics, as well as the distance between existing AD plants and the feedstock sources. Therefore, it is crucial to appraise the environmental performance using life cycle assessment (LCA). The LCA method has been used to evaluate the environmental impacts of production of biomethane from grass silage and cattle slurry in Ireland [13]; pig manure in China [14]; livestock manure and agricultural residue in Italy [15]; agricultural residue such as straws in Italy, France, Germany, Sweden and the United States [16]; cattle manure and municipal solid waste in Germany [17]; maize and willow in Sweden [18]; urban biowaste in France [19]; household organic waste in Sweden [20]; and food waste in the UK [21,22]. To date, there has been no study that links LCA and feedstock scenarios in Northern Ireland, when in fact quantification of the environmental impacts of increased biomethane production is especially important in Northern Ireland due to the pressure on multiple sectors with regards to decarbonisation and environmental sustainability.

1.3. Focus of paper

This research paper builds on previous studies by conducting spatial mapping *and* LCA to evaluate the potential of biomethane for the decarbonisation of the gas grid in Northern Ireland. The study aims to measure how AD could be used to capture a proportion of the energy value that would otherwise be lost as diffuse emissions (e.g. CO_2 and methane) from already existing or underutilised systems and aid in the delivery of a more resilient and decarbonised gas system as part of a possible green growth pathway. More specifically the paper sets out to:

(i) Conduct spatial mapping of manure and silage feedstock quantities, as well as associated biomethane potential values at a townland zone scale in Northern Ireland. Note that townlands are a relatively small geographical area, common within Ireland, which are typically 100–500 acres in size.
(ii) Compare biomethane potential values from manure and silage feedstock with gas distribution network demands 2020–2021, for the existing 15 gas distribution network sections.
(iii) Perform a LCA to provide robust evidence to evaluate the increased production and utilisation of biomethane for the sustainable decarbonisation of gas. The LCA method is used to measure the impacts of different scenarios on the natural environment and resources.

2. Methods and data sources

2.1. Study area: Northern Ireland

In 2019, Northern Ireland accounted for 4.7% of the UK greenhouse gas emissions, while accounting for only 2.8% of the UK population over the same period [23]. One reason for this disproportionate contribution is that despite Northern Ireland's small population of 1.88 million, its food output equated to protein requirements of 10 million people in the same year, with an associated value of £5.4 billion [24]. Agriculture therefore plays a vital role in the region's economy, contributing around 5% of Gross Value Added and 5% of total employment [25]. Regardless of this, there is no doubt that a heavy focus on GHG emissions reduction is required in Northern Ireland if targets are to be met in relation to decarbonisation and net zero carbon pathways.

The high intensity of farming (driven largely by the high demand for agricultural products produced in Northern Ireland) coupled with relatively low but growing gas demand per capita (3.8 MWh compared to 7.5 MWh per person in Great Britain), places Northern Ireland in a unique position to decarbonise the gas grid through the increased utilisation of existing agricultural biomass to produce biomethane. Such a transition from natural gas to biomethane links with the Common Agricultural Policy Strategic Plans to promote biomethane production from livestock manure, residues, and underutilised grassland [26].

The rerouting of manure to AD facilities, along with the opportunity to support nutrient recovery and collection, provides a route of increased control and more efficient redistribution of nutrients from surplus to deficit areas or further afield. This would be valuable for sustainable agriculture development due to the surplus phosphorus pool that exists in Northern Ireland at present [27]; and the legacy effect of which has resulted in a high proportion of soils with levels of crop-available phosphorus which are above the agronomic optimum recommended for grassland (38% of all agricultural soils, 50% within the dairy sector) [28].

2.2. Spatial mapping of agricultural feedstocks and associated biomethane potentials

2.2.1. Livestock manure

For this study livestock numbers were sourced from the Agricultural Census in Northern Ireland (results for June 2020) to provide cattle, pig and poultry numbers at a farm scale [29]. On each farm, using Table 1, the quantity of livestock in each category was converted to an associated volume of manure produced over a one-year period. In Northern Ireland, cattle conventionally graze on grassland and are brought in during the winter months when grass growth has significantly reduced. The exact housing period for cattle depends on several factors including annual weather patterns and unique farm management decisions. As the minimum slurry storage capacity on holdings in Northern Ireland is 22 weeks, the housing period was set at 22 weeks for all cattle categories. For pig and poultry livestock the housing period was the whole year.

The total mass of manure was then estimated according to Eq. (1) and considering density as 1000 kg/m^3 [10,32].

$$M = \sum_{l=1}^{n} P_l \times M_l \times H_l \qquad \text{(Eq. 1)}$$

where,

M = Total livestock manure production (tonnes/year)
M_l = Manure production for livestock type l (tonnes/head/year)

Table 1
Volume of excreta produced per animal in each livestock category per week [30,31].

Livestock category	m^3	Livestock category	m^3	Livestock category	m^3
Cattle		Pig		Poultry (1000 birds)	
Dairy cow	0.37	Sows in pig	0.08	Laying birds	0.81
Dairy female 2 year + other	0.23	Gilts in pig	0.05	Growing pullets	0.405
Dairy female 1–2 year	0.18	Other sows	0.08	Hatching egg producers	0.81
Beef cow	0.23	Boars	0.05	Broilers	0.81
Beef female 2 year + other	0.23	Maiden gilts	0.05	Turkeys	1
Beef female 1–2 year	0.18	Cull sows	0.08	Geese	0.7
Bulls over 2 years	0.23	Finishers	0.03	Ducks	0.7
Bulls 1–2 years	0.18	Weaners growers	0.05	Other	0.81
Male over 2 years	0.23	Suckling	0.01		
Male 1–2 years	0.18				
Males 6–12 months	0.09				
Dairy female 6–12 months	0.09				
Beef female 6–12 months	0.09				
Male under 6 months	0.05				
Dairy female under 6 months	0.05				
Beef female under 6 months	0.05				

P_l = Animal population in head count (heads)
H_l = Housing period for animal type l (ratio of housing period to full year)

2.2.2. Underutilised grass silage

Total mass of ‘underutilised’ grass silage was estimated for each farm by comparing the level of livestock grass silage dry matter (DM) requirement with a maximum target threshold of utilisable grass (Eq.(2)). The maximum target was assumed to be 10 tonnes (t) DM/hectare (ha) as different sources support this grass yield [8,33]. Similarly, Teagasc (the Agricultural and Food Development Authority in Ireland) also launched the “Grass10” initiative (2017–2020), with the aim of achieving 10 t DM/ha-year on Irish livestock farms.

Grassland area per farm was sourced from DAERA [29], and severely disadvantaged areas were removed from the final area. Animal grass silage dry matter requirements were estimated using Table 2, adapted from McEniry et al. [34]. A quantity of underutilised silage material per farm was calculated by comparing the farm DM requirement value with the maximum target quantity of useable grass (10 t DM/ha). Farms with a DM requirement level which exceeded the target level were assigned zero underutilised silage material, as there is limited evidence to suggest that a yield over the target threshold is sustainable in the long term.

$$DM_f = DM_{fgs} \times A - \left(\sum_{l=1}^{n} P_l \times F_l\right) \qquad \text{(Eq.2)}$$

where,

DM_f = Underutilised grass silage dry matter produced at a farm (tonnes/year)
DM_{fgs} = Total utilisable grass silage dry matter produced at a farm (tonnes/ha/year)
A = Area of farm (ha)
P_l = Animal population in head count (heads)
F_l = Grass silage dry matter required for feed for animal type l (tonnes/head/year)

2.2.3. Biomethane potential

The calculated farm scale mass of livestock manure and underutilised silage material were then converted to biomethane potentials using conversion factors listed in Table 3. Further to this, Eqs. (3) and (4) were used to estimate the biomethane potential from the manure and underutilised silage material. Maps for quantities of manure and silage material, as well as the associated biomethane potential were prepared in a Geographic Information System (GIS). Farm data was plotted in GIS using the farm specific

Table 2
Total dry matter requirement per year for each livestock unit for feeding [34].

Livestock category	Total dry matter requirement (t/year)	Livestock category	Total dry matter requirement (t/year)
Dairy cow	6.39	Ewes	0.819
Dairy female 2 year + other	5.28	Rams	0.737
Dairy female 1–2 year	5.28	Other sheep 1 year and over (Breeding)	0.737
Beef cow	5.28	Other sheep 1 year and over (other)	0.737
Beef female 2 year + other	2.82	Lambs under 1 year	0.287
Beef female 1–2 year	2.82		
Bulls over 2 years	5.28		
Bulls 1–2 years	5.28		
Male over 2 years	2.458		
Male 1–2 years	3.851		
Males 6–12 months	1.566		
Dairy female 6–12 months	1.58		
Beef female 6–12 months	1.58		
Male under 6 months	1.566		
Dairy female under 6 months	1.58		
Beef female under 6 months	1.58		

Table 3
Conversion factors for livestock population and grass silage to biomethane potential.

Feedstock	TS (%)	VS (% of TS)	Methane yield (Nm^3/t VS)	Methane yield per tonne of fresh mass of feedstock (Nm^3)
Cattle manure	8.5[a]	80[a]	215.5[c]	14.7
Pig manure	5.5[b]	80[b]	328[c]	14.4
Poultry manure	50.5[d]	80[a]	330[c]	133.3
Grass silage	29.27[e]	91[f]	400[f]	106.5

[a] Scarlat et al. [10].
[b] Curry et al. [35].
[c] Average of Scarlat et al. [10] and Melikoglu and Menekse [36].
[d] calculated by considering number of birds in each category from agricultural census [29].
[e] Gray et al. [37].
[f] Ó Céileachair et al. [8]. TS: Total solids, VS: Volatile solids.

co-ordinates and then summed together at a townland zone scale to create spatial data for each variable.

$$B_{lm} = \sum_{l=1}^{n} M_l \times TS_l \times VS_l \times MY_l \qquad \text{(Eq. 3)}$$

$$\mathrm{B_{gs}} = \mathrm{DM_f} \times \mathrm{ODM} \times \mathrm{SY} \qquad \text{(Eq. 4)}$$

where,

$\mathrm{B_{lm}}$ = Biomethane potential from livestock manure (Nm^3/year)
$\mathrm{M_l}$ = Manure production for livestock type l (tonnes/head/year)
$\mathrm{TS_l}$ = Total solids content in the manure produced from animal type l (%)
$\mathrm{VS_l}$ = Volatile solids content in the manure produced from animal type l (%)
$\mathrm{MY_l}$ = Biomethane potential (CH_4 Nm^3/tonne VS)
$\mathrm{B_{gs}}$ = Biomethane potential from underutilised grass silage (Nm^3/year)
ODM = Organic dry matter content of the silage (%)
SY = Biomethane potential for silage (CH_4 Nm^3/tonne organic DM)

2.2.4. Comparison between biomethane potential and annual natural gas distribution network demand

Total gross biomethane potential was then converted to energy potential by considering biomethane calorific value as 10 kWh/Nm^3 methane content, without the enrichment of propane. Methane content of upgraded biomethane was taken as 97% [37]. For biomethane enriched with propane, a calorific value of 39.2 MJ/Nm^3 (10.88 kWh/Nm^3) was considered (neglecting possible minor changes in density or volume of the biomethane produced due to propanation). Propanation, i.e. the addition of propane, is carried out if there are any short-falls in the calorific value of biomethane. It should be noted that these estimations considered maximum biomethane energy potential and any parasitic load or use of biomethane during the production process itself were not accounted (which were incorporated at Northern Ireland scale in LCA calculations in **Section 2.3** and **Section 3.3**).

The energy potential from livestock manure and underutilised silage biomethane was then compared with annual natural gas distribution energy demand (Oct 2020–Sept 2021) in Northern Ireland, to measure the potential displacement of fossil natural gas by biomethane.

Following the comparison of biomethane energy to the annual gas distribution network energy demand at Northern Ireland scale, this exercise was then repeated for 15 gas network sections. These network zones were created by carving the gas distribution network into 15 different zones based on the location of existing offtake points, and a radius of 10 km was drawn around each. Fig. 1 shows the 15 gas distribution network zones used for the comparison analysis, any overlap has been removed and apportioned equally to the relevant zones. Here 10 km was chosen as it was deemed a reasonable distance that considers the movement of feedstock and the biomethane itself. The different zones were centered on a gas network section with an associated 2020/2021 natural gas distribution demand value assigned to each. The zone distribution demand value was then compared to the biomethane potential value from manure and underutilised silage in the radius area.

2.3. Life cycle assessment

2.3.1. Goal and scope

Life cycle assessment was utilised to evaluate the opportunity for AD to support gas grid decarbonisation and nutrient recovery. The goal of carrying out a LCA was to evaluate environmental impacts of the bioenergy produced over the entire production chain. Life cycle assessment is an effective framework that sits at the interface of science, engineering and policy [38–40]. The four main stages defined by ISO 14040 and IS0 14044 for conducting LCA are: (i) goal and scope definition, (ii) life cycle inventory analysis, (iii) environmental impact assessment, and (iv) life cycle interpretation [41,42].

The LCA was conducted using SimaPro v9 software and Ecoinvent database. This study used a cradle-to-grave attributional approach and did not include environmental impacts due to infrastructure processes associated with production of equipment, which is in line with the approach used by Duan et al. [14]. Attributional approach focuses on describing environmentally relevant physical flows to and from a life cycle and its subsystems. In LCA, the functional unit is a measure of the purpose of the studied system and it provides a reference by which the inputs and outputs can be related i.e., enables the comparison between different systems [43]. The functional unit was set at 1 MJ of energy produced, to account for the bioenergy produced and evaluate how the biomethane from livestock manure and underutilised grass silage can lead to decarbonisation. Three scenarios were considered for LCA (Fig. 2):

- **Scenario 1/base line scenario**: Represents what is predominantly occurring i.e. all housed livestock manure produced is stored and applied to land with no treatment
- **Scenario 2**: Anaerobic digestion of housed livestock manure and underutilised silage
- **Scenario 3:** An integrated anaerobic digestion and pyrolysis system

2.3.2. Life cycle inventory analysis

The life cycle inventory analysis within a LCA involves

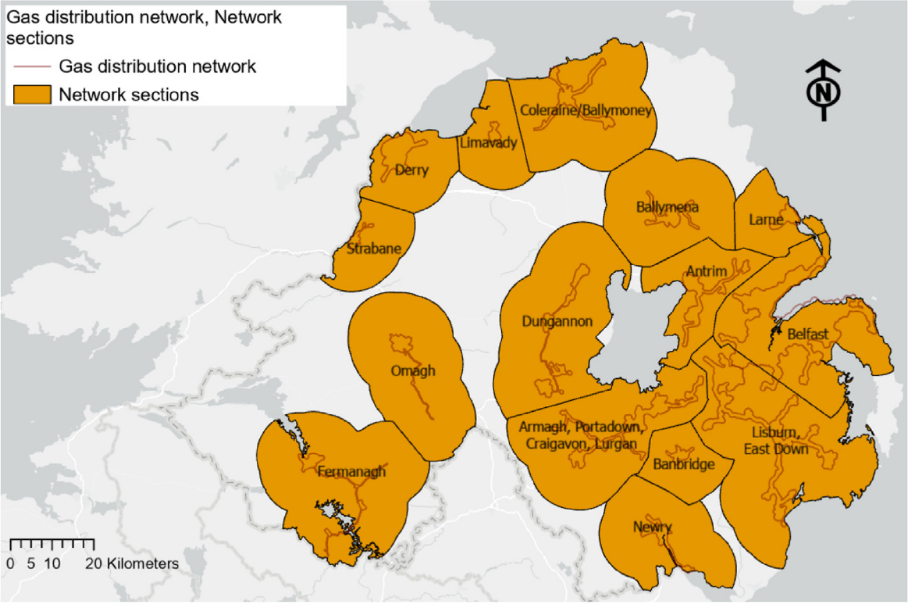

Fig. 1. The 15 gas distribution network zones carved to compare annual biomethane energy potential with the natural gas demand.

identifying and quantifying: (i) all resources used to produce the product, such as energy, water, raw materials, and processed materials; and (ii) all substances released into the environment, such as the emission of pollutants into the air, soil and water. Detailed information on the inventory components for the LCA carried out within this study are described in the subsections below.

2.3.2.1. Feedstock. The GHG emissions from manure storage and application to land are in the form of gases such as CO_2, CH_4 and N_2O, and were accounted for in this study over a 100-year time horizon with factors for biogenic CH_4 and N_2O as 28 kg CO_2 equivalent (kg CO_2 eq) and 264 kg CO_2 eq, respectively. The biogenic CO_2 emissions were not considered as the carbon content of the manure was previously captured by the crops [44]. The GHG emissions for 1 tonne of dairy and pig manure storage and application to land was considered as 46.0 kg CO_2 eq [32,45]. 1 tonne of poultry manure storage and application to land leads to GHG emissions of 276.6 kg CO_2 eq [46]. Emissions of non-methane volatile organic compounds were not a focus of this study.

Ammonia emissions for livestock manure storage and application to land were calculated using Tier 1 approach [47]. The Tier 1 approach is a simplified method that only requires livestock population data by animal category and climate region, in order to estimate emissions. This was performed by multiplying livestock number from the Agricultural Census in Northern Ireland and emission factors for ammonia per head (**Supplementary material: Table S1**). Total phosphorus loading was estimated by multiplying number of animals and phosphorus excretion rate per head [29,30]. The amount of P leached from manure storage and application to land was estimated to be 1% of the P loading [13].

The emissions related to manure storage and application to land were not considered for Scenario 2 and 3 as the manure produced in these scenarios is used for energy production; in line with other studies [13,46].

A maximum transport distance of feedstock was set at 10 km, conservatively estimated between farms and anaerobic digestion facilities [37]. The energy and emissions incurred for transportation were modelled from Ecoinvent database for lorry units.

2.3.2.2. Anaerobic digestion. There are many kinds of digesters that can be utilised for on farm anaerobic digestion and here a continuously stirred tank reactor (CSTR) set up was assumed for biogas production. Typically, CSTRs operate in mesophilic conditions at a temperature of 38 °C and with a total solids (TS) content below 12%. For feedstocks with higher TS content the liquid digestate from a dewatering process may be recirculated. The parasitic heat demand of the digester for raising the temperature of feedstocks from 10 °C (average ambient temperature) to 38 °C, was calculated using Eq. (5). This thermal energy is often provided by the biogas produced on the farm [8]. The electrical energy required for production of biogas has been quantified as 10 kWh_e/t feedstock [37]. Wind energy, a prominent renewable source available locally, with minimal CO_2 emissions was considered to provide electrical energy for all the processes.

$$E_{thermal} = M_{feedstock} \times C_p \times \Delta T \tag{Eq. 5}$$

$$M_{digestate} = M_{feedstock} - \left(B \times 0.55 \times 0.716 + B \times 0.45 \times 1.96\right) kg/Nm^3 \tag{Eq. 6}$$

where,

B = Biomethane production potential (Nm^3)
$E_{thermal}$ = Parasitic heat demand (kJ)
$M_{feedstock}$ = Mass of feedstock anaerobically digested (kg)
$M_{digestate}$ = Mass of digestate produced after AD (kg)
C_p = specific capacity of feedstock, assumed as 4.18 kJ/kg/K
ΔT = 28 °C

The biogas composition was considered as 55% methane and 45% CO_2 (vol/vol). For calculating greenhouse gas emissions in kg, the density of methane and CO_2 were considered as 0.716 kg/Nm^3 and 1.96 kg/Nm^3 respectively.

2.3.2.3. Biogas to biomethane upgrading. Herein amine scrubbing was considered for biogas to biomethane upgrading. The thermal

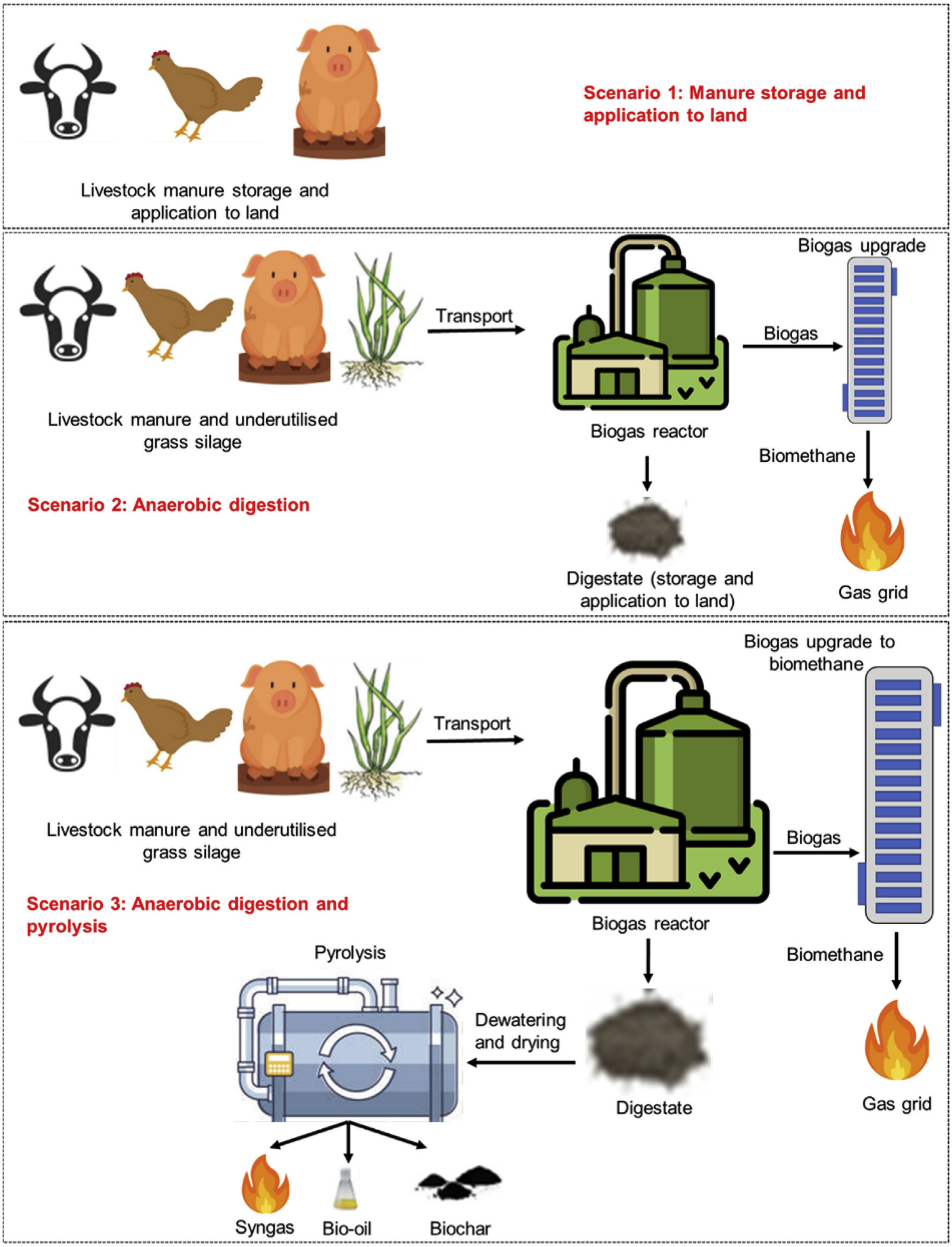

Fig. 2. The three scenarios and associated processes considered for life cycle assessment.

(0.45 kWh_{th}/Nm^3) and electrical energy demand (0.09 kWh_e/Nm^3) were estimated according to Wu et al. [48]. Biogas loss due to fugitive emissions was 1.5% and the biomethane produced after upgrade contained 97% of methane (10 kWh/Nm^3 calorific value) and 3% carbon dioxide [37].

2.3.2.4. Digestate. Mass of digestate produced during biogas production was calculated using Eq. (6) and GHG emissions due to digestate storage and spread on land (Scenario 2) were estimated as 57.14% of emissions from manure storage and spread on land. This is to account for carbon capture during biogas production [49]. Ammonia emissions for Scenario 2 were calculated by using ratio of digestate storage and application to manure storage and application [13].

For Scenario 3, the dewatering of digestate employed a decanter centrifuge for solid-liquid separation. Electrical energy required for centrifugation was modelled as 3.5 kWh_e/t of processed material [50]. The separation efficiencies for dry matter, N and P are presented in Supplementary material: Table S2 [51]. It was considered that the liquid fraction from this stage is spread on land leading to greenhouse gas emissions of 49.1%, 75.4% of N (attributing to ammonia emissions) and 36.1% of P from digestate. While the solid fraction is dried and subsequently pyrolysed.

Drying the digestate solid fraction was modelled considering a belt dryer system, as continuous and separated solids can be fed directly. The solids produced after drying, had energy content of 16.9 MJ/kg and contained 10 (wt)% liquids [15,50]. The thermal energy required was estimated according to Eq. (5) for raising the temperature from 25 °C to 105 °C and for evaporation (Eqs. (7) and (8)).

$$E_{\text{thermal evaporation}} = M_{\text{liquids removed}} \times C_v \tag{Eq. 7}$$

$$M_{\text{liquids removed}} = \text{Mass of liquids in solid fraction} - (\text{mass of dried solids produced} \times 0.1)\ (\text{kg}) \tag{Eq. 8}$$

where,

$E_{\text{thermal evaporation}}$ = Evaporation energy required (kJ)
$M_{\text{liquids removed}}$ = Mass of liquids removed (kg)
C_v = Latent heat of evaporation of water (2380 kJ/kg)

It has been studied that there are no associated losses of carbon and P during drying of digestate [52]. However, the same study found that, total N content is reduced by 50% due to emissions of 81–87% of ammonia nitrogen (as % of TS) from solid fraction of digestate to produced solids.

2.3.2.5. Pyrolysis of dried solids. In pyrolysis, the properties and quantities of product such as syngas, bio-oil and biochar are heavily influenced by the residence time, temperature and feedstock quality. Most waste-to-energy industrial units are operated at a temperature of 500–550 °C [53,54]. For this study, a pyrolysis system was modelled at 500 °C with yield of products (efficiency of 65%) in accordance with Monlau et al. [15]. This is also attributed to the fact that the stability of the organic carbon content in biochar reaches a maximum of 80% at 500 °C and thereafter remains constant with respect to the pyrolysis temperature [55]. The electrical energy required for pyrolysis was calculated as 10% of the energy content of the dried solids used as input to the pyrolytic system [56].

Based on this data every tonne of dried solids resulted in products which were syngas (86.6 kg), bio-oil (578.8 kg) and biochar (322.8 kg). The energy produced from pyrolysis was due to syngas (lower heating value of 15.7 MJ/Nm^3) and bio-oil (higher heating value of 23.5 MJ/kg) (Table 4). It was considered that the products from pyrolysis would be combusted with an efficiency of 75% to provide energy for the drying of the digestate. There was a minor additional thermal energy (<0.25%) requirement for drying the solid fraction of digestate which was negligible and therefore removed from all further calculations.

2.3.3. Credit allocation

In this study, the credits were allocated by using mass allocation method. Credits were allocated to biomethane for replacing natural gas. Therefore, the reduction in greenhouse gas emissions was accounted for preventing natural gas extraction and combustion. Additionally, no credits were allocated to the use of manure and digestate as fertiliser [57]; and biochar as a soil amendment [46,58,59]. This is also because the quality of biochar would be dependent on the feedstock properties and processing options chosen and is outside the scope of this paper.

2.3.4. Sensitivity analysis

A sensitivity analysis was undertaken to understand the impacts of quantities of different categories of feedstock, i.e. cattle manure, pig manure, poultry manure and grass silage on the environmental impacts. Arguably, feedstocks with lower harmful environmental impacts should be paid greater attention for production and supply chain management to make biomethane generation more environmentally sustainable. It was conducted by quantifying variation in output in the environmental impact categories for a 10% variation in the input parameter (feedstock quantity).

3. Results

3.1. Spatial mapping of livestock manure and grass silage and associated biomethane potential

A value of 9218 kilo tonnes of manure from housed livestock which equates to 1162 kilo tonnes of total solids was estimated to be produced for the year 2020 (Fig. 3). The total fresh weight of underutilised silage was estimated as 4693 kilo tonnes which equates to 1374 kilo tonnes of dry matter of silage.

An annual production potential of 253 million Nm^3 of biomethane was estimated to come from anaerobic digestion of housed livestock manure material and biomethane from underutilised silage material was estimated to be 500 million Nm^3 (values rounded to the nearest million) (Fig. 4). The total gross biomethane potential from both manure and silage is therefore 753 million Nm^3.

3.2. Spatial mapping of biomethane energy potential

The total maximum biomethane potential from livestock manure and underutilised grass silage, equates to an energy equivalent of around 7300 GWh (considering biomethane calorific value as 10 kWh/Nm^3 methane content), without the enrichment of propane.

The energy potential from manure biomethane (253 million Nm^3) without assuming the addition of propane equates to 32% of the total gas distribution network energy demand, which was 7656 GWh between October 2020 and September 2021. Assuming the manure biomethane is enriched with propane to a calorific value of 10.88 kWh/Nm^3, the manure biomethane potential increases to 36% of the 2020–2021 demand. Underutilised silage biomethane represents 63% of the energy demand without the addition of propane, which increases to 71.1% of the gas distribution network energy demand (with enrichment of propane). The biomethane potential from both manure and underutilised silage biomethane combined is equivalent to 95% of the total gas distribution network energy demand without propane enrichment. This potential represents 107% of the 2020–2021 demand, after considering addition propanation.

Within the boundary of the 15 network distribution zones, i.e. 10 km from the gas distribution network, the total biomethane potential from manure and silage material was 209 million Nm^3 and 418 million Nm^3 which is equivalent to 79% of the total natural gas distribution network demand in 2020/21 (7656 GWh). Assuming the manure and underutilised silage biomethane (627 million Nm^3) is enriched with propane, the energy potential within the 15 zones accounts for 89% of the total demand (Table 5).

Biomethane potential from manure and underutilised silage displaced varying levels of gas demand in each of the 15 zones (Fig. 5, Supplementary material: Table S3).

Table 4
Biogas characteristics and energy values used for inventory analysis phase of life cycle assessment.

Energy and biogas details	Unit	Value
Energy for transportation of feedstock for 1 km distance	MJ/t	5.7
Transportation distance for feedstock	km	10
Thermal energy for raising temperature of feedstock by 1 °C	kJ/kg	4.18
Electrical energy for anaerobic digestion plant	kWh_e/t	10
Biogas composition	%	55% CH_4 45% CO_2
Density of methane	kg/Nm^3	0.716
Density of carbon dioxide	kg/Nm^3	1.96
Thermal energy for biogas to biomethane upgrade	kWh/Nm^3	0.45
Electrical energy for biogas to biomethane upgrade	kWh_e/Nm^3	0.09
Electrical energy for decanter centrifuge	kWh_e/t	3.5
Energy content of solids produced after belt dryer	kWh/kg	4.7
Electrical energy for pyrolysis of dried solids	As % of the energy content of input solids	10
Energy content of syngas	kWh/Nm^3	4.36
Energy content of bio-oil	kWh/kg	6.53

It is clear that biomethane from the anaerobic digestion of manure and underutilised silage material, if added to the gas distribution network, can displace a significant proportion of the current annual demand in Northern Ireland. Of the 15 zones, 11 would have sufficient production capacity to export gas to other zones. Only the Belfast, Derry/Londonderry, Fermanagh, and Larne areas would be net importers of biomethane.

3.3. Material and energy balance at Northern Ireland scale

Based on the details collated for inventory analysis (summarised in Section 2.3), a mass and energy balance was created at Northern Ireland scale. A comparison of the scenarios suggests the following.

Current livestock management i.e. 4693 kilo tonnes of manure storage and application of to land leads to no energy production.

In a scenario where all livestock manure and underutilised grass silage are used for anaerobic digestion, the energy required for transportation and raising the temperature of 13,911 kilo tonnes of feedstock from 10 °C to 38 °C was quantified as 220 GWh and 452 GWh_{th}, respectively. Biogas produced amounted to 1368 million Nm^3. This biogas, when passed through amine scrubbing for upgradation, required thermal energy (615 GWh_{th}) and electrical energy (123 GWh_e). Biomethane produced after upgrading was 97% methane leading to a total energy production of 6124 GWh (after consideration of the thermal energy requirements to be supplied from biomethane).

In an integrated anaerobic digestion and pyrolysis scenario, the total energy produced in the form of biomethane also amounts to an estimated 6124 GWh per year. The energy required for dewatering the digestate was calculated as 42.6 GWh_e. The drying energy required for the solid fraction of digestate was 1110 GWh_{th}. The produced solids needed 310 GWh_e for running the pyrolysis plant with an efficiency of 65%. The syngas (54 kilo tonnes) and bio-oil (356 kilo tonnes), when combusted with an efficiency of 75%, provided all the thermal energy required for drying the solid fraction of digestate i.e. due to the water content of the digestate. The quantity of biochar produced was estimated at 200 kilo tonnes (Table 6).

3.4. Life cycle assessment: environmental impact assessment and interpretation

3.4.1. Energy output and net energy ratio

The midpoint indicator assessment results showed that there was no output energy produced in base line scenario (Scenario 1) i.e., when all livestock manure produced is stored and applied to land with no treatment. However, the energy produced in AD (Scenario 2) and integrated AD and pyrolysis (Scenario 3) reached 6124 GWh. The net energy ratio calculated as ratio of output energy to input energy was 12.7 and 7.4 for Scenario 2 and 3, respectively (Fig. 6). The fossil cumulative energy demand, calculated by considering non-renewable sources of energy in the production chain was observed as 0 GWh (Scenario 1) and −5904 GWh due to energy credits (Scenario 2 and 3).

3.4.2. Global warming potential

Current livestock manure management, without any treatment, leads to global warming potential for a 100-year horizon of 653 kilo tonnes CO_2 eq (housing period of cattle as 22 weeks), which is ~13% of total GHG emissions from agriculture sector in Northern Ireland. While for the anaerobic digestion scenario, global warming potential of −879 kilo tonnes CO_2 eq was observed. This was because of the GHG emissions incurred (in kilo tonnes CO_2 eq) during transportation (56), biogas loss (226), biomethane combustion for thermal energy (0.23), wind energy for electricity for biogas plant operations (1) and replacing natural gas by biomethane (−1541). Digestate (12,164 kilo tonnes) when spread on land can cause 377 kilo tonnes CO_2 eq.

GHG emissions in kilo tonnes CO_2 eq in Scenario 3 were due to the anaerobic digestion process (Scenario 2) and wind energy during dewatering (0.5), liquid fraction spread on land (205), biomethane combustion for dried solids production (0.4), pyrolysis (3) and syngas combustion (33).

To put the impacts of all the three scenarios in the Northern Ireland population context, the global warming potential was 344 kg CO_2 eq/person, −464 kg CO_2 eq/person and −563 kg CO_2 eq/person (population of Northern Ireland for the year 2020 [63]). To put it into the context of functional unit, the global warming potential was −40 g CO_2 eq/MJ (Scenario 2) and −50 g CO_2 eq/MJ of bioenergy produced (Scenario 3).

3.4.3. Ammonia emissions

Nitrogen excreted by animals forms the source of emissions during manure storage and application to land leading to 18.2 kilo tonnes of ammonia emissions (Scenario 1). When manure is anaerobically treated, it can lead to a small increase in ammonia emissions due to the mineralisation of organic N through the digestion process [13]. This was observed in the findings where ammonia emissions were quantified as 18.8 kilo tonnes in Scenario 2. While in Scenario 3, 18.4 kilo tonnes of ammonia emissions were noted due to the liquid fraction application to land and losses during drying of solids. Ammonia emissions for 1 Functional unit (1 MJ of energy produced) were observed as 0.82 g (Scenario 1), 0.85 (Scenario 2), 0.83 g (Scenario 3). Furthermore, ammonia emissions contribute to terrestrial acidification due to deposition of N in nutrient forms to the land (Supplementary material: Table S4).

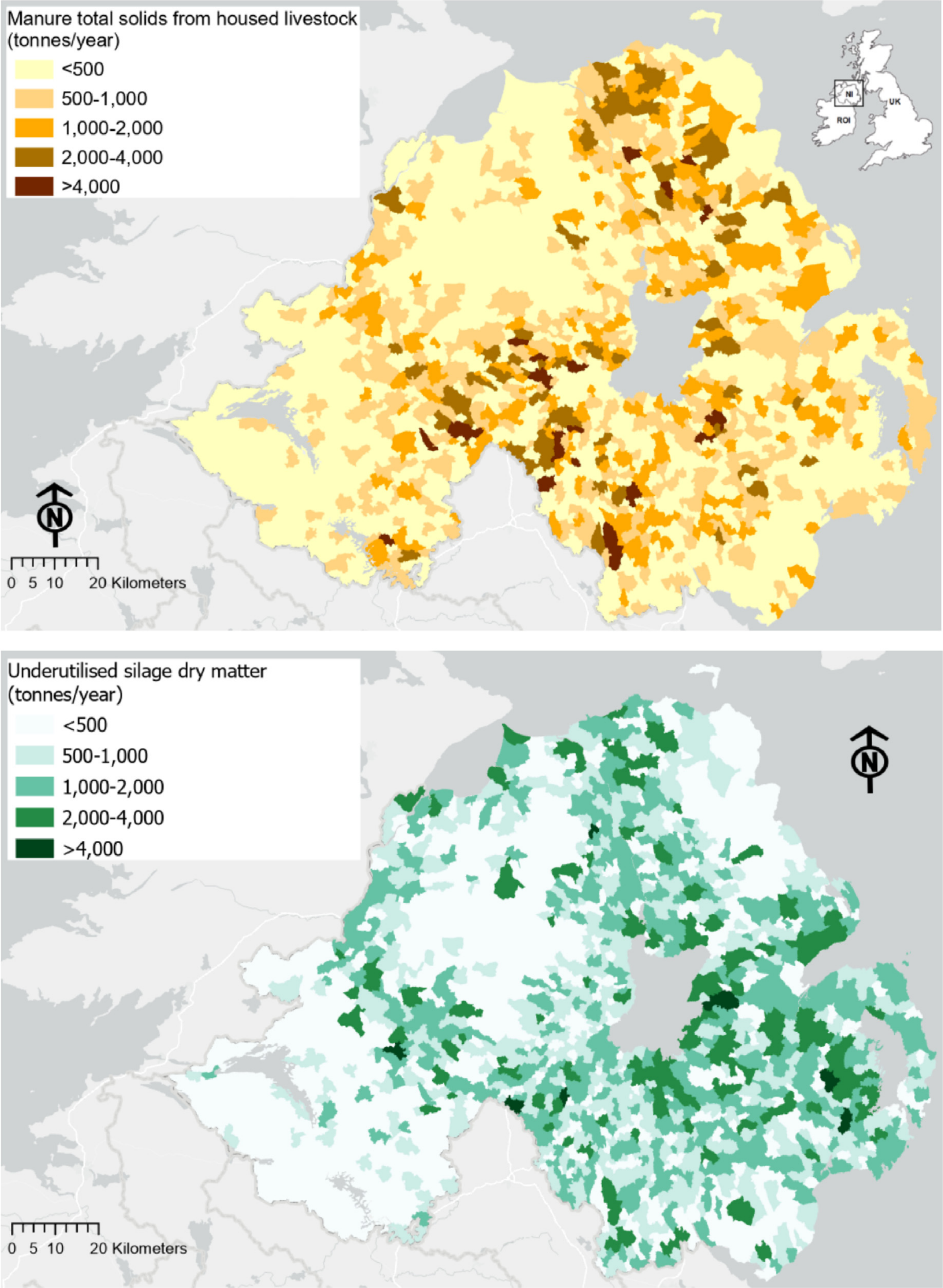

Fig. 3. Manure total solids from housed livestock over a one-year period and tonnes of underutilised silage dry matter in each townland zone.

3.4.4. Eutrophication potential

The eutrophication potential due to over fertilisation or excess supply of nutrients was quantified as 109 tonnes P eq for Scenario 1 (4.9 mg/MJ). Moreover, there was no variation observed due to anaerobic digestion. However, in Scenario 3 the solid-liquid separation and pyrolysis of dried digestate solid fraction led to locking of

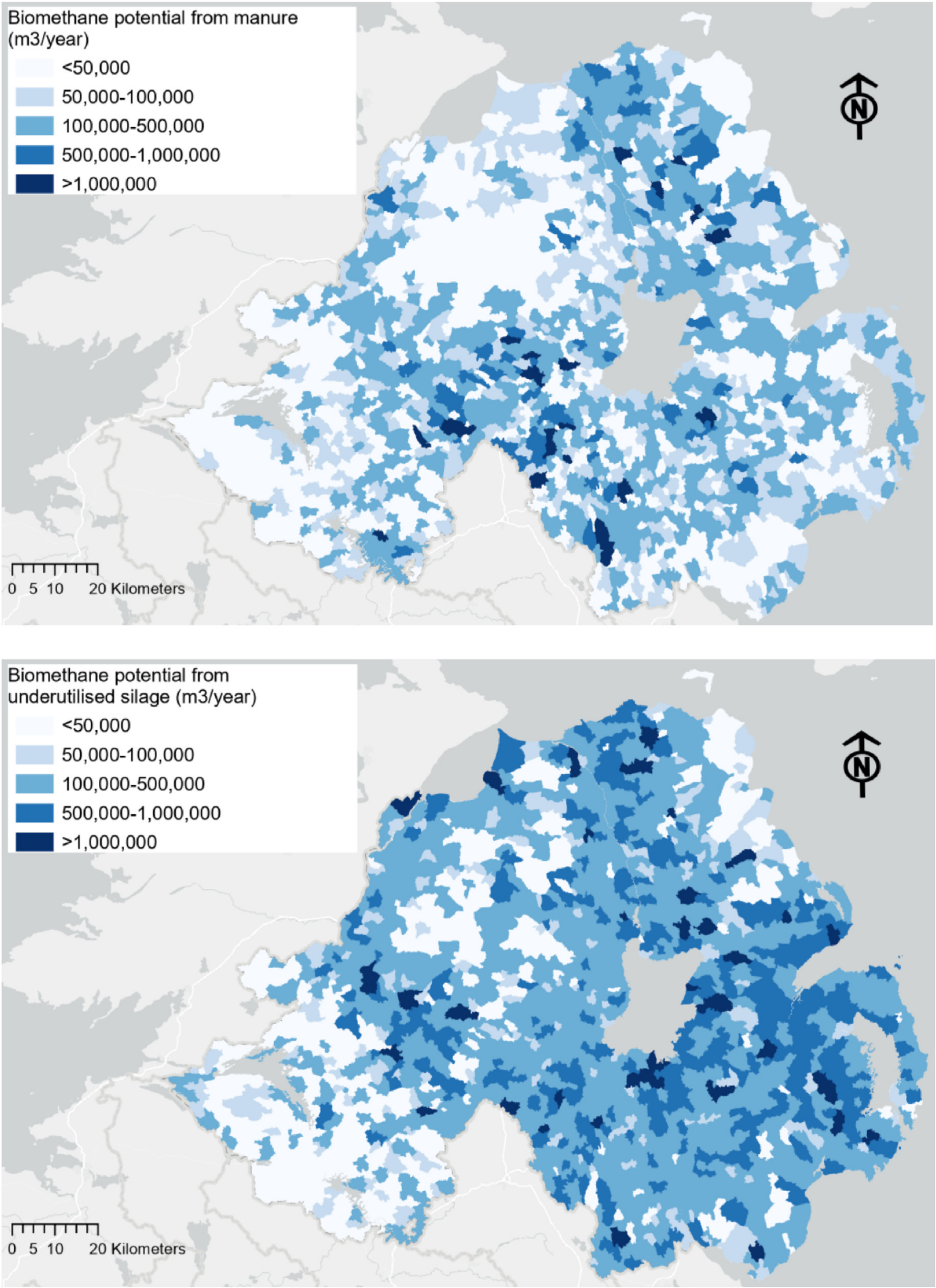

Fig. 4. Biomethane volumes over a one-year period from housed livestock manure and underutilised silage dry matter at a townland zone scale.

Table 5
Biomethane potential and contribution to total demand within the 15 network zones.

Energy values	Unit	Manure feedstock	Underutilised grass silage feedstock	Total (manure + silage)
Biomethane potential	Million Nm^3/year	209	418	627
Energy equivalent (without the enrichment of propane)	GWh/year	2027	4053	6080
Energy equivalent (with the enrichment of propane to a calorific value of 10.88 kWh/Nm^3)	GWh/year	2275	4550	6825
Energy equivalent compared with gas distribution network energy demand between October 2020 and September 2021 in Northern Ireland (7656 GWh) (without the enrichment of propane)	%	26%	53%	79%
Energy equivalent as a % of gas distribution network energy demand between October 2020 and September 2021 (7656 GWh) (with the enrichment of propane)	%	30%	59%	89%

Numbers may not add up due to rounding.

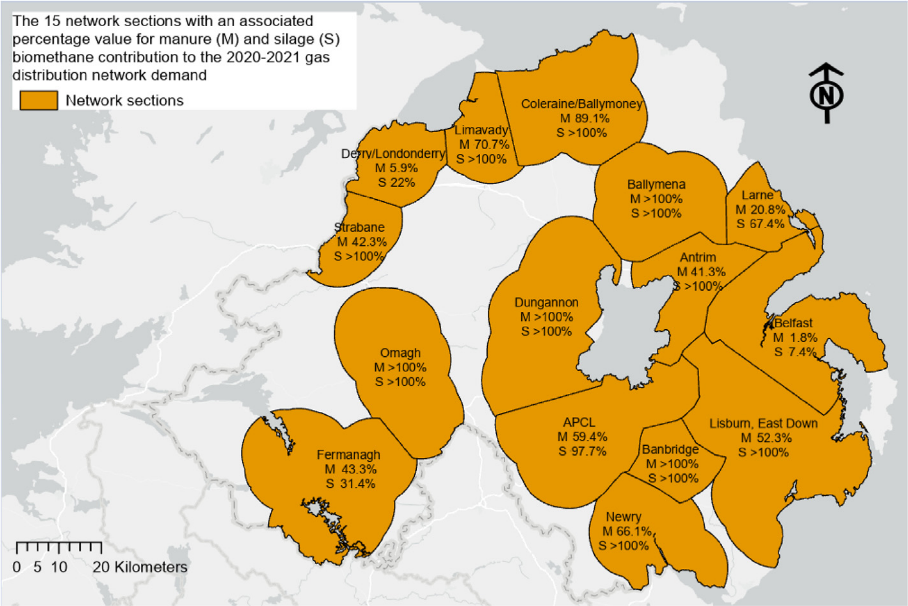

Fig. 5. The 15 gas distribution network zones. M = percentage of the 2020/21 energy distribution demand met by manure biomethane, S = percentage of the 2020/21 energy distribution demand met by silage biomethane. Assuming the enrichment of propane to a calorific value of 10.88 kWh/Nm^3.

P of biochar. This resulted in reduction of P leaching by 64% and thus resulting eutrophication potential as 39 tonnes P eq for a year (1.8 mg/MJ).

3.5. Sensitivity analysis

A sensitivity analysis was undertaken to investigate the impact of 10% variation of the quantity of livestock manure and grass silage on the environmental impacts. It was noted that out of all the feedstocks, the variation in the output was highest for grass silage quantities as shown in Tornado plots in Fig. 7. A 10% increase in use of grass silage can lead to an increase in production of energy by 6.9% and a decrease in net global warming potential of the biomethane production chain by 10.2% (Scenario 2) and 8.4% (Scenario 3). Increase in ammonia emissions and phosphorus leached (eutrophication potential) due to a 10% increase in the feedstock quantities are shown in Supplementary material: Table S5.

4. Discussion: contribution of a biomethane based decarbonisation approach to environmental sustainability

4.1. Providing renewable gas for decarbonisation of natural gas

To the best of the authors' knowledge this is the first study to conduct both spatial analysis *and* environmental emissions quantification through LCA to explore scenarios of gas decarbonisation. Although, the analysis was conducted on a regional level the methodology used is universal and can be applied elsewhere.

We identified that the total energy produced in the form of biomethane using manure from housed livestock and underutilised grass silage amounted to 6124 GWh which was ~80% of the natural gas demand for 2020–2021. This renewable gas can be delivered through a regional supply which is significantly decoupled from external geo-political factors.

The life cycle assessment considered the interdependencies between the processes to provide the evaluation of the total energy produced. The net energy ratio calculated as ratio of output energy to input energy was 12.7 for anaerobic digestion, and 7.4 for an integrated anaerobic digestion and pyrolysis. There is a growing interest in the biogas to biomethane upgrade for grid supply because of the difficulty in decarbonising fossil gas. In fact, Styles et al. [60] showed that supply of biomethane as renewable gas for heat has a better environmental performance compared to the supply of biomethane for electricity.

4.2. Anaerobic digestion and pyrolysis for nutrient circularity

Given the fact that the calculations in the present study were

Table 6
Mass and energy balance for use of livestock manure and underutilised grass silage for biomethane production for the year 2020.

Scenario	Process/parameter	Unit	Input	Output	Reference/calculation
S1	**Manure storage**				
S1	Grass silage	kt	4693		Section 3.1
	Livestock manure	kt	9218		Section 3.1
	GHG emissions	kt CO_2 eq		215	[32]
	Ammonia emissions	kt		13.5	Table S1
	Manure application to land				
	GHG emissions	kt CO_2 eq		438	[32]
	Ammonia emissions	kt		4.7	Table S1
	P leached	t P		109	t P leached = t P * 0.01 [60]
S2 and S**3**	**Biogas production**				
S2 and S**3**	Transportation of feedstock				
	Transportation	kt*km		139,105	[61]
	Fuel	GWh	220		Ecoinvent database
	GHG emissions	kt CO_2 eq		56	
	Anaerobic digestion				
	Thermal energy for feedstock temperature from 10 °C to 38 °C	GWh$_{th}$	452		[37]
	Electrical energy	GWh$_{e}$	139		[48]
	Biogas produced	Million Nm^3		1368	
	GHG emissions thermal energy	t CO_2 eq		173	Biomethane conversion factora
	Biogas to biomethane upgrade				
	Thermal energy	GWh$_{th}$	615		0.45 kWh/Nm^3 biogas processed [37]
	Electrical energy	GWh$_{e}$	123		0.09 kWh$_e$/Nm^3 biogas processed [37]
	Biogas loss (1.5%)	Million Nm^3		20	
	Biogas produced after losses	Million Nm^3		1348	
	GHG emissions due to biogas loss	kt CO_2 eq		226	
	Biomethane produced	Million Nm^3		741	
	Biomethane energy	GWh$_{th}$		7191	97% methane
	GHG emissions wind energy	kt CO_2 eq		1	0.003 kg/MJ
	GHG emissions thermal energy	t CO_2 eq		236	Biomethane conversion factor
	Negative GHG emissions for replacing natural gas	kt CO_2 eq		−1541	Conversion factors (biomethane and natural gas)[a]
Digestate storage and spread on land					
S2	Digestate	kt		12,164	Eq. 6
	GHG emissions	kt CO_2 eq		377	[49]
	Ammonia emissions (digestate)	kt		18.8	[13]
	P leached	t P		109	[60]
Dewatering of digestate					
S3	Digestate	kt	12,164		Eq. 6
	Energy decanter centrifuge	GWh$_{e}$	42.6		[50]
	Solid fraction	kt		1532	
	Liquid fraction	kt		1063	
	GHG emissions wind energy	kt CO_2 eq		0.5	0.003 kg/MJ (Ecoinvent database)
	GHG emissions (liquid fraction)	kt CO_2 eq		164	[49]
	Ammonia emissions (liquid fraction)	kt		14.2	[13]
	P leached due to liquid fraction	t P		39	[60]
	Dried solids production				
	Solid fraction	kt	1532		Section 2.3.4
	Energy (heating) from 25 °C to 105 °C	GWh$_{th}$	134		Eq. 5
	Evaporation energy	GWh$_{th}$	976		Eq. 7
	Produced solids (10% moisture content)	kt		619	
	Embedded energy in produced solids	GWh$_{th}$		3097	[15]
	GHG emissions thermal energy	t CO_2 eq		423	Biomethane conversion factor[a]
	Ammonia emissions (drying)	kt		4.2	[52]
	Pyrolysis of dried solids				
	Produced solids (10% moisture content)	kt	619		[15]
	Electrical Energy (10% of energy content of feedstock)	GWh$_{e}$	310		[56]
	GHG emissions wind energy	kt CO_2 eq		3	Ecoinvent database
	Syngas	kt		54	[15]
	Bio-oil	kt		356	
	Biochar	kt		200	
	Energy syngas (75% η)	GWh$_{th}$		187	
	Energy bio-oil (75% η)	GWh$_{th}$		1298	
	GHG emissions syngas	kt CO_2 eq		33	

[a] Greenhouse gas reporting: conversion factors 2021 [62]. S: Scenario.

based on worst-case scenarios, the total phosphorus in the digestate compared to the inputted feedstock largely remains the same in Scenario 2. However, the act of gathering manure material from a collective of farms, combined with strong decision support tools to better measure and monitor nutrient requirements at a farm scale, supports more efficient digestate and nutrient redistribution.

In a holistic system where the decarbonisation and nutrient management goals do not compete but are tackled together, the 70–80 number of currently operating AD agri-businesses could act as hubs in Northern Ireland. These hubs, in local co-ordination with the farming community, could reduce the over-supply of phosphorus to agricultural land and contribute to a greater circularity of

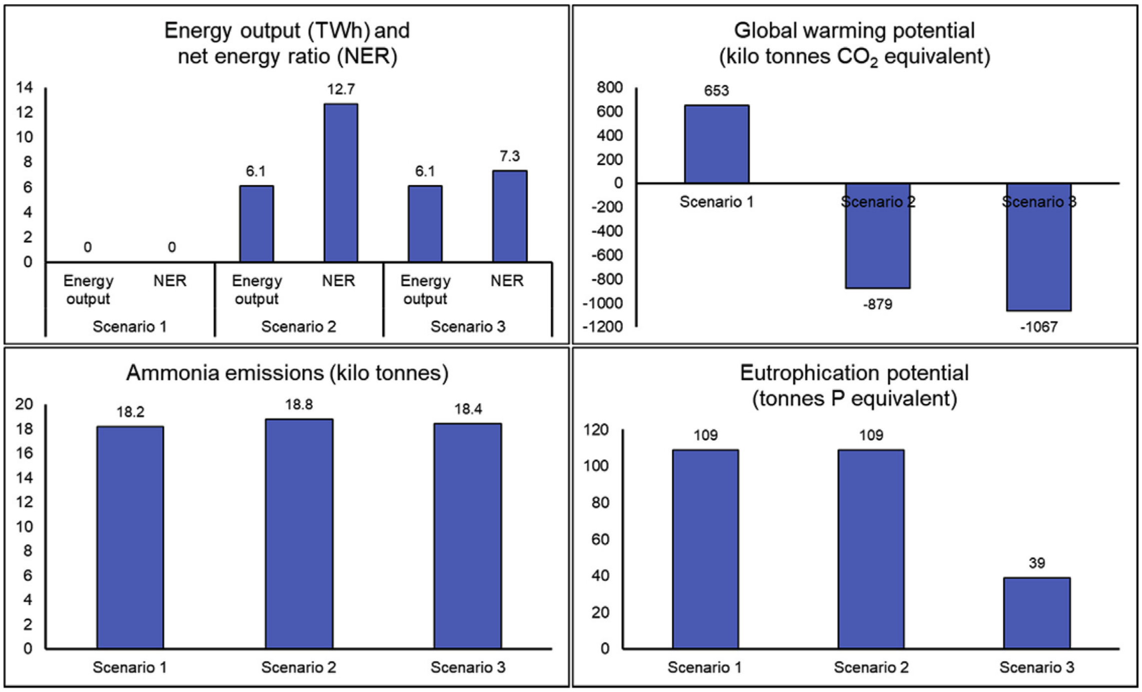

Fig. 6. Environmental impacts incurred for the year 2020, for Scenario 1 (no manure treatment), Scenario 2 (anaerobic digestion of livestock manure and underutilised grass silage) and Scenario 3 (anaerobic digestion and pyrolysis).

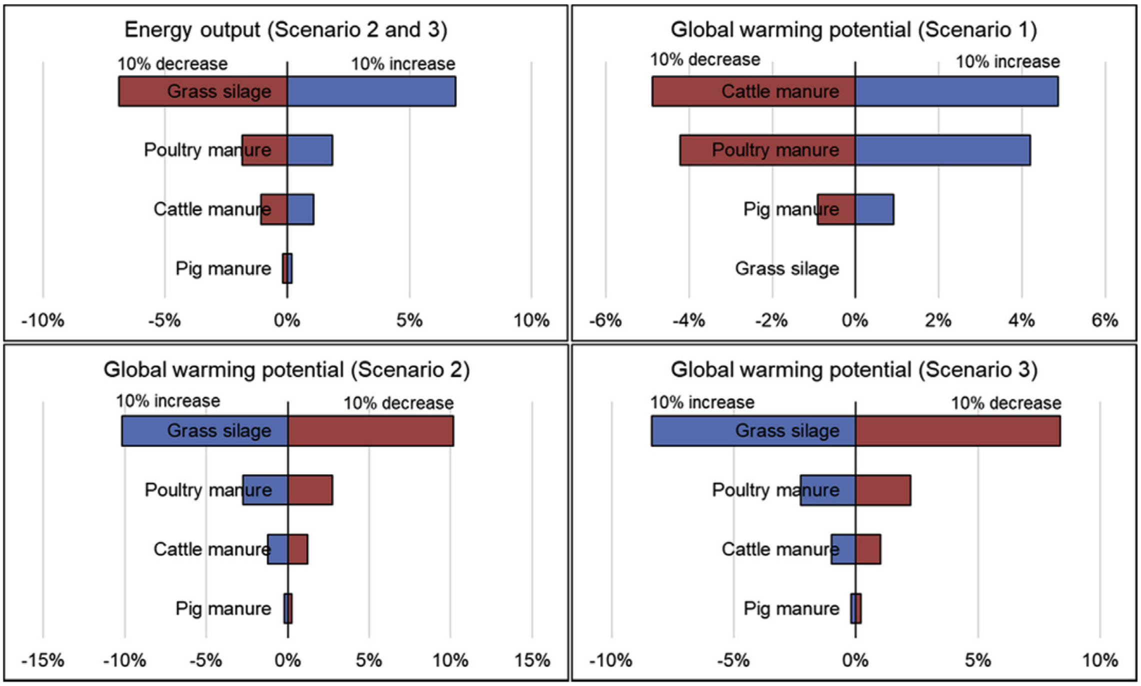

Fig. 7. Tornado plots present the extent to which the energy produced (as output) and global warming potential for biomethane production chain in Scenario 1, Scenario 2 and Scenario 3 are sensitive to a ±10% change in feedstock quantities.

phosphorus. The use of AD to therefore mine currently problematic nutrients from the agri-food system further supports longer term regional food security, and agricultural and environmental sustainability.

The biochar, a co-product of Scenario 3, represents a more nutrient dense material for more efficient redistribution. At the same time biochar is expected to contain about 64% of the original P of manure, which could be more easily controlled in terms of its reapplication to land or exported as a soil amendment material. To note, there are potential regulatory hurdles which will need to be overcome for these potential markets.

Going forward, it is crucial to conduct the economic analysis of the energy production scenarios and net-zero pathways. It is also recognised that pilot trials would be valuable in providing additional evidence to confirm the analysis presented in this study as well as the technical practicalities and resulting environmental benefits over time. Future studies would benefit from modelling of advanced fuel production processes.

5. Conclusions

This study provides a comprehensive assessment for gas grid decarbonisation by utilising biomethane from collected manure and grass silage. Spatial analysis conducted at a townland zone scale showed an availability of livestock manure and underutilised grass silage in quantities of 9218 kilo tonnes and 4693 kilo tonnes respectively. Further to this, life cycle assessment was conducted for three scenarios to evaluate the environmental impacts of biomethane based decarbonisation.

The first scenario showed the current state-of-play, where no energy was produced from agricultural feedstock and 653 kilo tonnes CO_2 equivalent of greenhouse gases are emitted.

In an anaerobic digestion scenario, 6124 GWh of energy was produced with a net energy ratio, calculated as ratio of output energy to input energy, of 12.7. The global warming potential was evaluated as −879 kilo tonnes of CO_2 equivalent.

In an anaerobic digestion and pyrolysis scenario, 6124 GWh of energy is produced. However, the energy ratio decreases to 7.4 due to the use of electrical energy during dewatering of digestate and its pyrolysis. The biochar produced is calculated as 200 kilo tonnes (retaining 64% of phosphorus from manure). Given the fact that assessment of biochar quality was beyond the scope of this study, no credits were allocated to biochar for conservative estimates.

A production of 6124 GWh due to biomethane in both the decarbonisation scenarios indicates that about 80% of the gas demand for the year 2020–2021 could be met with biomethane. The study also performed estimates of ammonia emissions and phosphorus leaching potentials for all the three scenarios.

CRediT authorship contribution statement

Neha Mehta: Life cycle assessment, Writing – original draft, Writing – review & editing. **Aine Anderson:** Spatial mapping, Writing – original draft, Writing – review & editing. **Christopher R. Johnston:** Supervision, Writing – review & editing. **David W. Rooney:** Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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