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Author(s)	Tisocco, Sofia;Lenehan, James J.;Zhan, Xinmin;Crosson, Paul
Publication Date	2025-02-13
Publisher	Elsevier
Repository DOI	https://doi.org/10.1016/j.biombioe.2025.107702

Biomass and Bioenergy 195 (2025) 107702

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

Financial assessment of integrating anaerobic digestion with cattle farming for biomethane production – Implications for farm economics and the supply chain

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ARTICLE INFO

Keywords:
Biomethane
Grass silage
Financial support
Livestock farming
Net present value
Payback period

ABSTRACT

Integrating anaerobic digestion (AD) into agriculture can support carbon neutrality and circular bioeconomy. However, economic benefits for stakeholders are crucial for implementing full-scale AD. This study assessed the financial implications of producing grass silage for AD on beef farms. It also assessed the financial viability of full-scale AD plants co-digesting grass silage and cattle slurry for biomethane, focusing on competitive grass silage pricing and support schemes. Results indicate that a grass silage price of €245/t dry matter (DM) is needed for competitiveness with beef production; this requires a biomethane certificate price of €0.12/kWh for the AD plant. At current prices (€0.098/kWh), the AD plant could afford €164/t DM for silage, requiring farm subsidies of €893/ha to cover price gaps. Methane yield of AD silage, along with biomethane certificate and silage prices, are key variables affecting the 20-year net present value of the AD plant. This study underscores the government's critical role in fostering a low-carbon livestock sector.

1. Introduction

Renewable energy sources have become crucial for addressing global challenges such as climate change, energy security and sustainable development [1]. Biomethane, a renewable gas produced from biogas upgrading, has gained significant attention as a potential substitute for fossil gas imports [2]. Biomethane can be directly injected into existing natural gas grid or used as a vehicle fuel in compressed (CNG) or liquefied natural gas (LNG) forms [3]. However, the adoption of biomethane as a renewable energy source currently requires substantial financial support to achieve competitiveness with fossil fuel markets [4]. Support schemes, such as renewable energy feed-in tariffs (REFIT), renewable energy obligations, and tax incentives, are crucial for promoting biomethane production and utilization. These policies provide stability and financial support for project developers and/or biomethane users, incentivizing investment and market growth [5]. The agricultural sector can play a key role in the biomethane market by providing feedstocks to an anaerobic digestion (AD) plant [6]. The provision of livestock slurry and grass silage from farms into a full-scale AD plant can guarantee the feedstock demand of the AD plant and may provide a business opportunity for farmers [7], while reducing greenhouse gas emissions (GHG) from the agricultural sector [8,9]. In our previous study [8], a farm configuration of a pasture-based beef farm was proposed to provide grass silage and slurry to a 40 GWh biomethane plant. A beef farm was selected due to its prevalence as the predominant grassland utilization activity in Ireland [10]. The arrangement for a 40 GWh biomethane plant consisted of 130 farms of 50 ha and a livestock unit (LU) of 2.1 LU/ha each, which assigned 85 % and 15 % of the land to livestock and grass silage for AD provision, respectively, to meet the annual feedstock demand of the AD plant [8].

The economic assessment of biogas and biomethane production from agricultural feedstocks have been carried out before [11–13]. At a farm scale, Geoghegan and O'Donoghue [12] assessed the private and social (through GHG emissions mitigation) return from displacing dairy, beef and tillage activities with bioenergy feedstocks (grass silage and short rotation coppice willow). The valuation of the social return through carbon dioxide (CO_2) pricing was found to be critical to make the latter activities competitive with conventional agricultural activities.

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https://doi.org/10.1016/j.biombioe.2025.107702
Received 27 September 2024; Received in revised form 16 January 2025; Accepted 8 February 2025
Available online 13 February 2025

However, the possible integration of activities (i.e., beef and grass silage for AD) into a single farm was not addressed, nor were the implications of cultivating bioenergy feedstocks on agricultural land, as marginal lands were assumed for producing grass silage. At a supply chain scale, Dennehy et al. [11] analyzed the economic feasibility of on-farm anaerobic mono and co-digestion of pig slurry and food waste (FW), using stochastic modelling to assess the impact of key parameters (REFIT, quantity of food waste treated, gate fees, and digestate disposal costs) on AD plant viability. Co-digestion on a farm size of 2607 sows was found to be the most economically viable, balancing high revenue potential with moderate capital expenditures and a stable food waste supply. From a farm and supply chain point of view, Ye et al. [14] evaluated how subsidies for farmers and bioenergy producers affect the economic viability of cassava-based bioenergy production. It was found that the decision to subsidize the farmer or the energy producer mainly depended on the subsidy budget, farmers' risk aversion, land capacity and yield uncertainty. In this context, a joint economic analysis of both the AD feedstock provision from a farm and the impacts of potential financial supports on both the AD plant and farm is crucial to understand their financial interactions.

Nevertheless, the economic implications of integrating AD into farm systems and producing biomethane from the co-digestion of cattle slurry and grass silage remain underexplored. Grass silage production for AD is often assumed to exceed livestock requirements [15,16] or be harvested on marginal lands [12], which refers to land not suitable for traditional agricultural activities. Therefore, there is a notable gap in understanding how grass silage produced specifically for AD (from now onwards referred to as AD silage) on agricultural land could contribute to farm revenue, as well as the economic implications of applying digestate to a livestock farm. Furthermore, the impact of financial support measures on the viability of agricultural-based biomethane production should also be examined; the combined analysis of the farm and supply chain offers a distinctive approach that has not been explored. Addressing these gaps is crucial for a thorough understanding of the economic feasibility and potential benefits of integrating AD into livestock farms, biomethane production and digestate management within the agricultural framework.

Thus, the aim of this paper was to (1) assess the economic impact of integrating AD into a livestock farm and determine the AD silage price needed to make this activity competitive with beef production, (2) carry out a supply chain cost-benefit analysis of a 40 GWh biomethane plant, and (3) determine the adequate support schemes needed to ensure the economic viability of producing biomethane from the full-scale co-digestion of cattle slurry and grass silage.

2. Materials and methods

2.1. Model implementation

2.1.1. Farm scale

Ireland was chosen as a case study, as the co-digestion of grass silage and cattle slurry is feasible due to the large potential availability of these feedstocks [17]. Additionally, there is a growing interest from farmers, industry and the government to produce biomethane from agricultural feedstocks and reduce GHG emissions from both the farm and energy sector [18].

The farm model implemented was the Grange Dairy Beef System Model (GDBSM), which allows the evaluation of biophysical, economic and GHG outputs from pasture-based dairy-beef production systems [19], with the addition of an AD submodel, as explained in detail by Tisocco et al. [8]. The farm system model consists of a commercial dairy-beef system, characterized by the February-born early-maturing (EM) progeny of dairy cows, which are subsequently slaughtered at 24 months of age. The AD-farm configuration implemented was also previously determined by Tisocco et al. [8], in which 130 farms of 50 ha each were needed to supply 43,019 tonnes of AD silage and 50,042 m^3 of slurry annually to a 40 GWh biomethane plant co-digesting AD silage and slurry at a volatile solids (VS) ratio of 4:1, respectively. 85 % of each farm (42.5 ha) was allocated for growing grass for livestock use, encompassing both grazing and the production of silage for winter cattle feed (from here onwards referred to as livestock silage). The remaining 15 % (7.5 ha) was allocated to produce AD silage. A typical soil index of 3 was assumed, which indicates optimal concentrations of phosphorus (P) and potassium (K) in the soil for plant uptake. Consequently, nutrient requirements were based on maintaining soil fertility by replacing the nutrients extracted during each harvest (maintenance fertilization). A total of 616.5 m^3 of digestate was applied to the livestock area of each farm, including areas designated for livestock silage and grazing [8]. After digestate application, a waiting period of seven weeks was assumed before mechanical harvesting, and four weeks before allowing animals to graze on the pasture.

The gross margin of the livestock area was calculated by accounting for the revenue from animal sales, animal purchase costs and direct costs, such as concentrate feeds, milk replacer and fertilizers. A complete list of incomes and costs is shown in Table S1. The price of beef was taken from Bord Bia, considering an average of cattle price for dairy-beef cattle of €4.82/kg [20]. Consequently, the gross margin (GM) from the livestock area was calculated as shown in Eq. (1):

$$\text{Gross margin livestock} = (\text{Livestock sales} - \text{purchase}) - \sum \text{Direct costs} \tag{1}$$

The silage production costs were derived from the Grange Feed Cost Model (GFCM), a static agro-economic model [21]. The livestock silage crop was modelled as a typical perennial ryegrass (PRG) with a total annual yield of 13.2 t DM/ha and 22 % losses, while the AD silage crop comprised a mixture of PRG and red clover (RC) with a total annual yield of 14.2 t DM/ha and 22 % losses [8]. A legume-based crop was selected as an AD feedstock given its capacity to fix biological nitrogen (N_2), thus reducing the need for inorganic N inputs; this option aligns with European regulatory standards for renewable energy production [22]. Both livestock and AD silage costs included fertilizer purchase, harvesting and covering, and grassland management (Table S1). However, in the case of AD silage, the total price that the farms ask for should not only include the silage production cost but an additional amount to compensate for the partial displacement of the livestock enterprise (15 %). Therefore, the gross margin from a conventional livestock system (100 % Livestock) was also calculated. This parameter was used to determine the revenue difference between the two livestock systems (100 % Livestock and 85 % Livestock), which had to be compensated through the AD silage price in addition to the production cost, as shown in Eq. (2):

$$\text{Profit needed from AD silage} = \frac{50\text{ ha} * \text{GM } 100\%\text{L } (€/\text{ha}) - 42.5\text{ ha} * \text{GM } 85\%\text{L } (€/\text{ha})}{7.5\text{ ha}} \tag{2}$$

where GM 100%L and GM 85%L refer to the gross margin from the conventional beef farm (100 % Livestock) and AD-integrated farms (85 % Livestock), respectively.

Hence, the total price of AD silage needed per tonne (t) of dry matter (DM) was calculated from the sum of the production cost and the profit needed, as shown in Eq. (3):

$$\text{Total AD silage price} = \frac{\text{Production cost } (€/\text{ha}) + \text{Profit needed } (€/\text{ha})}{\text{AD silage yield } (\text{t DM}/\text{ha})} \tag{3}$$

2.1.2. Supply chain scale

The AD plant processes and parameters are detailed by Tisocco et al. [8]; in this study, a comprehensive analysis of the financial aspects associated with a 40 GWh biomethane plant was conducted. The capital (CAPEX) and operational (OPEX) expenditures of the AD plant are shown in Table S2. CAPEX included construction costs (digester, digestate storage and other civil works), biogas upgrading unit (pressure swing adsorption) and connection to the gas grid, among other costs (Table S2), while OPEX included plant operation and maintenance (O&M), upgrading plant maintenance, electricity purchase from the grid, administration costs, AD silage production and transport of feedstock and digestate. A straight-line depreciation method with a salvage value of 5 % was applied, alongside a corporation tax rate of 12.5 % in Ireland [23]. As some of the costs were estimated per unit of the reactor size [11], the size of the reactor was calculated using Eq. (4):

$$\text{Tank size } (m^3) = \frac{\text{volume fed annually } (m^3)}{365 \text{ d}} * \text{HRT (d)} \tag{4}$$

A hydraulic retention time (HRT) of 50 days was chosen, as indicated by Dennehy et al. [11], and a density of grass silage of 1 t/m^3 was assumed [8]. To evaluate the potential profitability of the AD plant, a net present value (NPV) was calculated. The NPV represents the difference between the present value of cash inflows and outflows associated with the project, discounted to the present time using a predetermined discount rate, as shown in Eq. (5):

$$\text{Net present value } (€) = -C_{op} + \sum_{t=1}^{n} \frac{R_t - C_t}{(1+r)^t} \tag{5}$$

where C_{op} refers to the capital costs; R_t and C_t denote the annual cash inflows and outflows, respectively; r indicates the discounted rate, which was set at 6 % as per industry practice [11]; and t is the project lifespan, which was taken as 20 years [18]. A positive NPV indicates that the investment is expected to generate more cash inflows than outflows, indicating potential profitability. Conversely, a negative NPV implies a potential financial loss. A zero NPV reflects that the investment is expected to break even.

The values for various AD plant parameters were sourced from existing literature (Table S2) and were adjusted to October 2023 by applying an inflation rate. This adjustment involved multiplying the original prices by their respective inflation rate, calculated using the price index from each respective year obtained from the Central Statistics Office (CSO), as depicted in Eq. (6):

$$\text{Price}_c(€) = \text{Price}_p(€) * \left(\frac{\text{Index}_c}{\text{Index}_p}\right) \tag{6}$$

where c refers to the current year and p to a previous year.

The market price of natural gas has experienced significant fluctuations in recent years (Fig. S1); for this study, a fixed value of €0.04/kWh was utilized for the market price of biomethane, which is reflective of Western Europe prices [24]. On top of the market price, financial supports were included to determine the final price paid for biomethane (Section 2.2). The investigation of CO_2 capture and storage as a revenue stream to biomethane plants has gained prominence due to its status as a limited biogenic CO_2 source [25]. However, given that CO_2 commercialization is still in the development stage [26], the latter scenario was not included in this analysis.

Financial support

In Ireland, the Renewable Transport Fuel Obligation (RTFO) is available for biomethane used as a vehicle fuel [27]. The National Oil Reserves Agency (NORA) issues a certificate for each MJ of renewable fuels introduced into the transportation market in the Republic of Ireland that complies with a life cycle assessment (LCA) performed by an EU Voluntary Scheme, following the Renewable Energy Directive (RED II) criteria [18]. RTFO certificates are traded among road transport fuel suppliers in Ireland, with prices determined by supply and demand, as well as the buy-out price applied to any blending shortfall. In this study, a certificate price of €0.098/kWh was applied, based on data obtained from Gas Networks Ireland (O'Riordan, 2023). Additionally, AD plants may receive CAPEX grants, with EU funding typically ranging from 20 % to 40 % of total costs, covering physical CAPEX, such as construction costs and civil work [28]. For this analysis, a physical CAPEX grant of 20 % was assumed. Furthermore, gas grid connection grants, covering an average of 30 % of total connection costs, were included, based on data provided by Gas Networks Ireland [18].

At a farm level, subsidies have been historically important for the subsistence of many farms throughout Ireland and Europe [29]. While this financial support is predominantly funded directly by the EU, and tend to be disbursed per animal or per hectare basis, national governments can also provide targeted support measures. The Irish government has recently proposed financial assistance for farmers establishing red clover swards, referred to as the red clover silage measure, with a specified payment rate of €300/ha [30]. Considering that red clover swards are typically established every five years [31], the annual subsidy for AD silage can be considered as €60/ha/year.

Therefore, to assess the impact of this specific farm subsidy for AD sward establishment, alongside existing support mechanisms within the supply chain, two main scenarios were considered to determine their overall profitability. The first scenario, referred to as the Baseline scenario, only included the biomethane certificate as available financial support for the AD plant. In contrast, the Grants scenario incorporated both the previously mentioned AD plant grants and the AD silage establishment grant, in addition to the biomethane certificate.

2.2. AD silage price dynamics in farm and AD plant

In the context of this study, it is crucial to examine the dynamic interaction between the AD silage price required by the farm and the price that the AD plant can afford to ensure a favourable financial situation. While the AD silage price requested by the farm is influenced by various farm parameters (Section 2.1.1), the AD plant's capacity to pay for the silage depends on its financial cash flows, which are impacted by the two scenarios being analyzed (Section 2.2).

This complex relationship underscores the challenge of establishing a pricing strategy that benefits both the farm's economic requirements and the AD plant's financial limitations across the considered scenarios. The determination of an acceptable payback period, referring to the year in which the NPV reaches zero and the investment cost is recovered, significantly influences investment decisions [32]. Previous studies have identified attractive business opportunities for AD plants with payback periods ranging from 5 to 10 years [11,31,32]. Thus, the maximum price that an AD plant, with cash outflows C_t, could afford for AD silage to achieve breakeven in a specific year, was determined according to Eq. (7):

$$0 = -C_0 + \sum_{t=1}^{n} \frac{R_t - C_t}{(1+r)^t} \tag{7}$$

with t set to 8 years, considering this payback period as an intermediate between those sourced from the literature [11,32,33] and one acceptable to the industry. Given the assumption of fixed annual cash inflows (R_t) and other constant cash outflows (e.g., maintenance and transport costs), the only annual variable cost to determine was the AD silage purchase cost. The detailed equation development is outlined in the Supplementary Material (Eq. (S1)).

2.3. Sensitivity analysis

A sensitivity analysis was conducted to assess the influence of fluctuations in key parameters on the final NPV. ±20 % variations in beef price and AD silage yield were separately assessed, as they would indirectly affect the AD silage price (Section 2.1.1). Furthermore, variations of ±20 % were applied to the biomethane certificate price, CAPEX grant and gas grid connection grants, as well as the biogas yield of AD silage, which was represented by the biochemical methane potential (BMP).

These variations reflect potential changes in management practices, government policies and market conditions, which could significantly impact the financial outcomes of the project [34,35]. Each parameter underwent individual variations during the analysis, with the rest of the parameters fixed at their default assumptions.

3. Results and discussion

3.1. Model implementation

3.1.1. Farm scale

Results from the calculation of the gross margin from the livestock area, both for the conventional beef farm (100 % Livestock) and the AD-integrated beef farms (85 % Livestock – 15 % AD), are presented in Table 1. It was found that the livestock area of the AD-integrated farms incurred 4 % lower direct costs compared to those of the conventional farm. The differences were mainly due to reduced application of chemical N, P and K fertilizers in the grazing and livestock silage area. As the digestate returned to the livestock area (616.5 m^3) contained more nutrients and greater volume than the slurry produced (454.2 m^3), due to the incorporation of grass silage into the feedstock mix [8], the application of chemical N, P and K fertilizers was reduced by 65 %, 33 % and 56 %, respectively [8]. This resulted in fertilizer savings from the grazing area of €12/ha and €27/ha for protected urea and 0:10:20 fertilizer (NPK compound), respectively (Table S3), leading to a 41 % reduction in costs compared to the conventional beef farm (Table 1). For the livestock silage area, fertilizer savings were €26/ha and €21/ha for protected urea and 0:7:30 fertilizer (NPK compound), respectively. Despite higher fertilizer savings in this area (Table S3), overall savings of producing livestock silage in the AD-integrated farms were 24 % when compared to the conventional beef farm. This was attributed to unchanged harvesting and grassland management costs, which accounted for 68 % and 89 % of the total livestock silage costs (Fig. S2). Similarly, during an assessment of the economic potential of transitioning specialized conventional arable farms to organic farming using biogas digestate, Freytag et al. [36] found that variable costs from various organic crop systems were 3 %–34 % lower than those in conventional farming; this reduction was primarily attributed to lower expenditures on pesticides and fertilizers. Additionally, in that study, revenues were higher in some scenarios due to the combination of lower direct costs, higher profits from premium prices, and the presence of a farm subsidy for organic farming. In the present study, digestate spreading costs were 50 % higher compared to slurry spreading (Table 1), due to the higher volume applied [8]. However, the absolute variation of digestate spreading costs was lower than those variations from grazing and livestock silage, making this cost less significant to the overall direct costs (Table 1).

Table 1
Gross margin of the livestock area from a conventional beef farm (100 % Livestock) and the farm analyzed during this study (85 % Livestock – 15 % AD).

Parameter	100 % Livestock (€/ha)	85 % Livestock – 15 % AD (€/ha)	Difference (%) [a]
Livestock area			
Direct incomes			
Livestock sales	4252	4252	0 %
Livestock purchase	626	626	0 %
Total direct incomes	3627	3627	0 %
Direct costs			
Concentrate feeds	1032	1032	0 %
Grazing [b]	96	57	−41 %
Livestock silage [c]	199	152	−24 %
Milk replacer	240	240	0 %
Slurry/Digestate application	20	30	50 %
Straw	21	21	0 %
Veterinary and medicine	185	185	0 %
Reseeding	96	96	0 %
Marketing and transport	79	79	0 %
Total variable costs	1967	1892	−4%
Gross margin	1659	1734	5 %
AD silage area			
Production cost	–	1480 (€134/t DM)	–
Gross margin difference [d]	–	1235 (€111/t DM)	–
Total AD silage price (€/t DM) [e]	–	245	–

[a] Calculated as (100 % Livestock - 85 % Livestock–15 % AD)/100 % Livestock.
[b] Costs incurred in fertilizer and lime application.
[c] Costs incurred in fertilizer and lime application, harvesting and cover.
[d] Calculated as Eq. (2).
[e] Calculated as Eq. (3).

Ultimately, the gross margin per ha from the AD-integrated farms was 5 % higher than the conventional beef farm; however, the total livestock gross margin per farm (50 ha) was 11 % lower than that of the conventional beef farm. This difference was attributed to the reduced number of hectares containing livestock in the AD-integrated farm (7.5 ha less, which corresponded to the AD silage cultivation). Consequently, the livestock gross margin gap was compensated through the AD silage price (Section 2.1.1). The costs of producing AD silage and the gross margin gap are shown in Table 1. A total price of €245/t DM (€61/t wet weight assuming a 25 % DM) was required to cover the production cost and to compensate for the reduced gross margin per farm. This value is higher than other prices reported in the literature, ranging from €113/t DM to €169/t DM [13,37,38], in which marginal lands were assumed for grass silage production or the grass was produced in excess of livestock requirements; consequently, the AD silage price only covered the production cost. During this study, the cost of producing AD silage was found to be €134/t DM (€33/t wet weight), which aligns with previous findings [13,37,38]. The additional price to compensate for the reduced gross margin from the beef enterprise was €111/t DM; this adjustment aimed to compensate for a 15 % livestock destocking, with beef price also playing a role in contributing to this gap (Section 3.4).

The final AD silage price requested by the beef farm can be covered through farm subsidies, paid by the AD plant or ultimately through a combination of both (Section 3.2 and 3.3). Considering €300/ha for establishing RC silage, the final price paid by the AD plant for the AD silage in the grants scenario decreased to €240/t DM, with the AD silage establishment grant covering only 2 % of the total price. This study provided valuable insights into the economic implications of producing AD silage on agricultural land; however, given that a commercial beef farm was analyzed, the final price needed for AD silage to achieve competitiveness with the current agricultural activity was probably higher than on a less productive beef farm. Nevertheless, the number of farms required to meet the AD plant's feedstock demand was lower than that would be required on a less productive farm; this aspect is crucial, considering the potential competition between food and energy. In the farm system modelled, it was calculated that if the entire 5.7 TWh of biomethane targeted for Ireland in 2030 [38] is produced through the co-digestion of grass silage and cattle slurry, a total of 121,250 ha would be required for AD silage production [8], which represents about 2.7 % of Ireland's current agricultural area utilized (AAU) [17]. In summary, achieving a balance between price and farmland availability is crucial for optimizing slurry and AD silage provision within different farm systems. The methodology outlined in this paper and in Tisocco et al. [8] can be transferable to different farm productivities.

3.1.2. Supply chain scale

The CAPEX and OPEX of the 40 GWh biomethane plant and the AD plant's operating parameters are detailed in Table 2 and Table S4, respectively. The highest share of the total CAPEX was attributed to the digester construction, constituting 23 % of the overall expenditure, followed by the gas grid connection and additional civil works, with 17 % and 16 % of the total CAPEX, respectively. The cost share is similar to

Table 2
Capital (CAPEX) and operational (OPEX) expenditure from a 40 GWh biomethane plant co-digesting grass silage and cattle slurry (baseline scenario).

Parameter	Total costs (€)	Annual costs (€/year)
CAPEX		
Digester construction	3,076,221	296,370
Digestate storage	476,775	45,934
Additional site civil work	2,122,543	204,491
Feedstock reception	182,590	17,591
Pasteurization	347,755	33,504
Upgrading plant	2,104,897	202,791
Connection to the gas grid	2,284,153	220,061
Development costs	529,747	51,037
Insurance	423,797	40,830
Contingency	1,059,493	102,074
Engineering	741,645	71,452
Total CAPEX	13,349,617	1,286,133
OPEX		
Plant O + M		61,573
Digester maintenance		46,148
Upgrading plant maintenance		196,006
Labour		145,455
Electricity		412,758
Administration		39,935
Feedstock transport		127,027
Digestate transport		114,324
AD silage production		2,633,549
Total OPEX		3,776,776
Income from biomethane [a]		4,734,034

[a] Total biomethane produced was 34,324,493 kWh.

Dennehy et al. [11], in which the digester construction and additional civil works accounted on average for 51 % of the total CAPEX during the assessment of an on-farm AD plant producing 10,489 MWh and 3509 MWh of electricity and heat, respectively, through a combined heat and power (CHP) plant (1.19 MW_e size). However, in contrast to Dennehy et al. [11], in which the CHP unit and distribution costs comprised 10 % of the total CAPEX, the upgrading plant and gas grid connection costs from this study constituted 32 % of the total CAPEX. These elevated costs are consistent with similar challenges faced in other European countries, as evidenced by experiences in the Danish biomethane industry [39], in which biogas upgrading and gas grid connection costs can add up to 30 % of the total CAPEX. This limitation is further compounded by the relatively underdeveloped gas grid infrastructure in Ireland [18], thereby constraining biomethane production within farm-scale AD plants. Similarly, in Brazil, a significant barrier to the expansion of natural gas and biomethane production lies in the high costs and logistical challenges associated with gas grid infrastructure development [40]. In this context, Gil-Carrera et al. [41] proposed an off-grid upgrading unit for farm-scale AD plants without nearby gas injection points to reduce upgrading and gas grid connection costs. Their model involved a mobile upgrading unit shared among multiple farm-scale biomethane plants, delivering biomethane to a central injection point. However, for full-scale AD plants with higher gas flows, the mobile unit's limited storage capacity may be insufficient, making grants a potential more viable option (Section 3.2).

AD silage purchase costs, paid to the farms, which included production expenses (i.e., fertilizer and harvesting costs) and additional costs to compensate for destocking (Section 3.1.1), accounted for 69 % of the total OPEX. The significant contribution of AD silage cost to agricultural-based biomethane plants has been outlined in previous studies [13,37]. For instance, Huerta et al. [37] reported AD silage costs ranging from 34 % to 66 % of the total OPEX in an abatement cost assessment of biogas upgrading from the co-digestion of grass silage and cattle slurry. However, grass silage also significantly contributes to biomethane production during co-digestion with cattle slurry, which is primarily attributed to its higher VS and BMP [13,42]. For instance, in the present study, AD silage contributed to 88 % of the total biomethane produced, which resulted in biomethane sales. Moreover, in contrast to maize silage, which has been negatively associated with land intensification and pesticide use [43], the utilization of legume-based AD silage offers an opportunity for farm diversification and GHG emission reduction at a farm level [8,9].

In the baseline scenario, the primary source of income of the AD plant was biomethane, with a total assumed price of €0.138/kWh, consisting of both the market (€0.04/kWh) and certificate price (€0.098/kWh). The NPV at year 20 was -€2,625,562, indicating that selling biomethane at that price was insufficient for financial competitiveness (Fig. 1); therefore, further financial support measures were analyzed (Sections 3.2 and 3.3). During this study, the digestate was not assigned an explicit economic value due to the closed loop modelled between farms providing feedstock and the AD plant [8]. Its value was indirectly reflected in fertilizer savings from AD-integrated farms (Section 3.1.1). The availability of land for digestate application is crucial for the economic viability of the AD plant [8,9]. Processing and commercializing digestate products from solid and liquid fractions of the digestate can enhance economic outcomes by reducing transport costs and adding value [44]. As previously mentioned, this study did not consider CO_2 capture and commercialization due to its under-development market and associated uncertainties [25]. Nevertheless, strategically valorizing diverse products from the biogas plant is crucial for enhancing business opportunities and improving the economic viability of the AD facility. This approach can diversify revenue streams and reduce long-term dependence on external financial support [45].

Financial support

Incorporating grants and the AD silage establishment subsidy in the analysis resulted in a 20-year NPV of €356,012 (Fig. 1). As stated in Section 3.1.2, gas grid connection costs represented 17 % of the total CAPEX, primarily due to the underdeveloped gas grid connection infrastructure in Ireland; thus, incorporating grants to cover part of these expenses could benefit AD plant operators. However, this scenario remained unattractive to investors, as the payback period was up to 19 years (Fig. 1). To assess the biomethane certificate price needed to achieve a more appealing business model, determined by a payback period of 8 years as outlined in Section 2.3, the annual revenue (R_t) required for financial viability was calculated using Eq. (S2). Physical CAPEX and gas grid connection grants were fixed at 20 %, and 30 %, respectively, as well as the AD silage establishment subsidy (€60/ha/year). The analysis indicated that an annual revenue of € €5,541,766

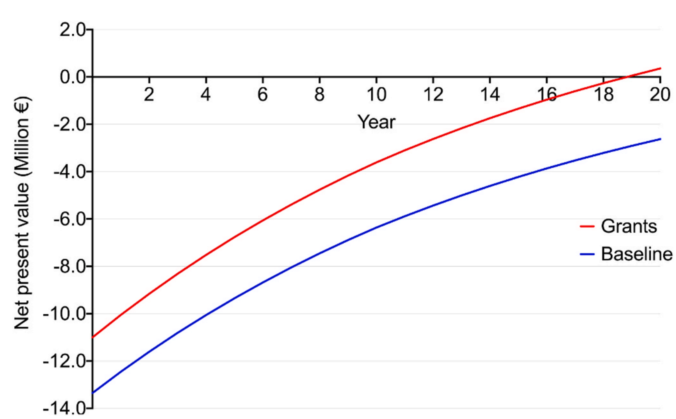

Fig. 1. Net present value (NPV) analysis over the 20-year project lifespan for the baseline scenario (only biomethane certificate price of €0.098/kWh available) and grants scenario (biomethane certificate price of €0.098/kWh, 30 % capital expenditure grant, 20 % gas grid connection grants, and red clover silage establishment subsidy of €300/ha every 5 years). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

would be necessary to achieve an NPV of 0 by year 8. Given the assumed fixed biomethane production and market price (€0.04/kWh), this would require a biomethane certificate price of €0.12/kWh, representing a 24 % increase from the baseline certificate price (€0.098/kWh). Alternatively, grants of 67 % would be necessary for both physical CAPEX and gas grid connection to achieve a payback period of 8 years, assuming a fixed biomethane certificate price of €0.098/kWh (as calculated following Eq. (S3)). Though both scenarios achieved an 8-year payback period, the 20-year NPV was higher in the case that the biomethane certificate price was €0.12/kWh (Fig. 2a). This was primarily attributed to the period after the payback (from year 8 onwards), during which higher revenues were generated from biomethane compared to the scenario with 67 % grants (Fig. 2a). Thus, analyzing different financial parameters is crucial for a comprehensive financial situation [46].

3.2. AD silage price dynamics in farm and AD plant

Ye et al. [14] examined subsidy allocation between farmers and bioenergy producers in China's cassava-based bioenergy industry. Their study revealed that subsidizing energy producers enabled the industry to afford higher biomass feedstock prices, while subsidizing farmers ensured their financial stability under high risk aversion and yield uncertainty. Additionally, farm subsidies indirectly benefited bioenergy suppliers by lowering feedstock costs [14]. The present study assumed that the AD plant would cover either the full cost (100 %) or nearly all the cost (98 %, including the AD silage establishment grant) for AD silage, as outlined in the baseline and grants scenarios, respectively. However, neither scenario proved financially attractive. The link between the AD silage price required by the farms and the price the AD plant could afford to achieve an 8-year payback period was further examined. While the former price depended only on farm parameters, such as AD silage production costs and gross margin from the livestock area (as outlined in Section 2.1.1), the latter price was partially determined by the maximum cash outflows that the AD plant could allow to achieve the acceptable payback period (Section 2.3). The maximum price the AD plant could pay was also influenced by the cash inflows; consequently, both the baseline and grants scenarios were taken into account, as they would impact the cash balance. The price gap to cover, calculated as the difference between the AD silage price required by the farm and the price that the AD plant could afford, would dictate the necessary AD farm subsidy. Results from this analysis are depicted in Fig. 2b. For both the baseline and grants scenarios, the AD plant could afford a maximum AD silage price of €127 and €164/t DM, respectively, to achieve an 8-year payback period. Consequently, price gaps of €118/t DM and €81/t DM would demand total AD farm subsidies of €1303/ha and €893/ha, respectively, for the 7.5 ha allocated for AD silage production (Fig. 2b and Table S5). These subsidies exceed Ireland's average direct payment rate of €421/ha [10]. In the latter scenario (where €164/t DM is paid for AD silage, assuming a biomethane certificate price of €0.098/KWh and grants available), the 20-year NPV equalled the one in which the biomethane certificate price was paid at €0.12/kWh (Fig. 2a). In both scenarios, the 20-year NPV exceeded the NPV in which 67 % of grants were available (with biomethane certificate and AD silage prices of €0.098/kWh and €240/t DM, respectively) due to the years following the payback period (from year 8 onwards), in which higher cash flows were obtained due to increased revenues (higher certificate price) or reduced OPEX (lower AD silage price).

In this context, achieving a balanced combination of financial support for both the farm and supply chain could enhance economic stability for both parties. The novelty of the present study lies in examining the connection between farm and AD plant economics, particularly concerning AD silage pricing. The decision to provide subsidies will depend on the size of the subsidy pool and government budget constraints, as well as competing funding priorities and resource allocation [14,47].

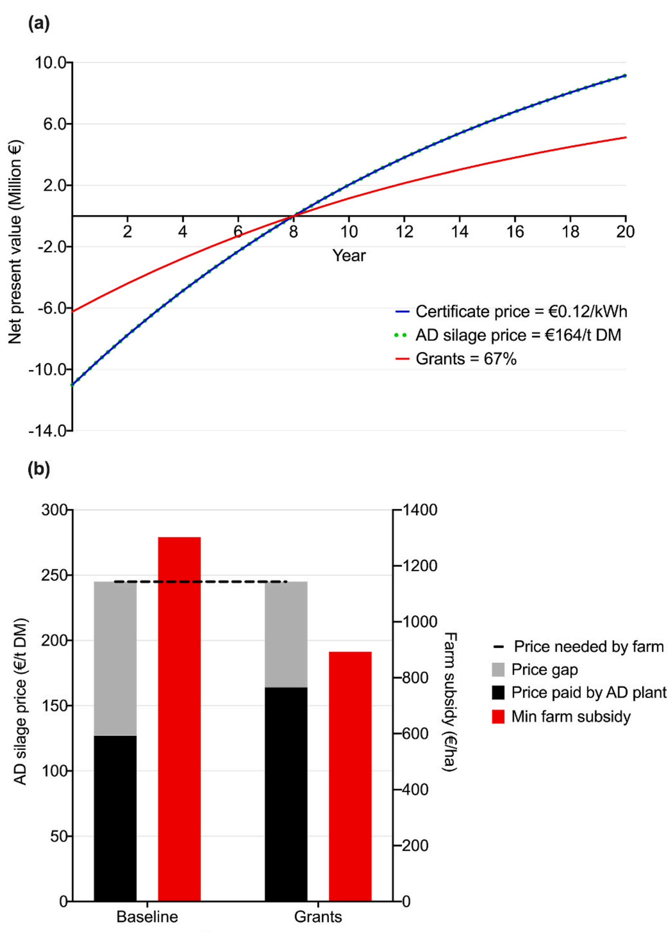

Fig. 2. (a) Net present value over the 20-year project lifespan with parameter values set to achieve a payback period of 8 years; (b) Maximum AD silage price paid by the AD plant to achieve an NPV of 0 by year 8 and minimum farm subsidy required to bridge the price gap with farm.

3.3. Sensitivity analysis

A comprehensive sensitivity analysis was conducted to evaluate the impact of parameter variability on the 20-year NPV, and the results are shown in Fig. 3. The BMP from AD silage and the biomethane certificate price emerged as the most influential parameters affecting NPV variations. A 20 % reduction on the methane yield from AD silage, which may be possible due to potential methane production reduction in full-scale

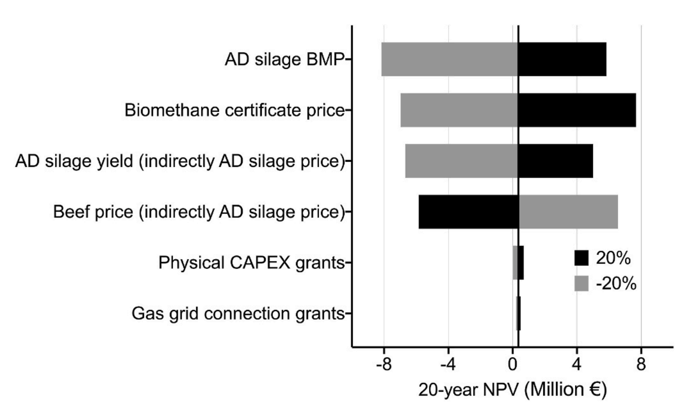

Fig. 3. Impact of a ±20 % variation in different model parameters on the 20-year net present value (NPV) of the AD plant.

AD [48], resulted in a negative 2393 % variation on the NPV. This was caused by an increase of AD silage production costs, given that 25 % more silage had to be purchased to compensate for the lower methane yields. A ±20 % change in the biomethane certificate price resulted in 2057 % variations of the 20-year NPV. Potential fluctuation in the biomethane certificate price may originate from government budget policies [47,49]. Li et al. [49] also identified the biomethane price as a critical parameter during the economic analysis of agri-waste co-digestion, wherein the NPV fluctuated by at least 80 % in response to a ±20 % variation in the biomethane price. The substantial NPV variation in our study likely derives from biomethane being the only potential revenue source for the AD plant, whereas Li et al. [49] included both biomethane and digestate sales, with digestate sale variations having a comparable impact on NPV as the biomethane price.

The AD silage yield was identified as the third most influential parameter, which indirectly affected the AD silage price (Fig. 3). A 20 % decrease in AD silage yields led to a negative 1974 % variation in the 20-year NPV, while a 20 % increase resulted in a positive 1308 % NPV variation. This uneven NPV variation originated from AD silage production costs, which varied by −17 % and 25 % in response to a +20 % and −20 % AD silage yield change, respectively (Table S6). Changes in silage yields could result from enhanced management practices [35] or varying weather conditions [50,51]. For instance, extreme weather events such as droughts or flooding, driven by a changing climate, can adversely affect grass growth and its effective utilization on farmlands [50,51]. As a result, variations in grass yields could influence the performance of the AD system by affecting silage availability, which in turn may alter biomethane production and impact the overall efficiency and viability of the system.

The beef price influenced the AD silage price required by the farms, and consequently, the price paid by the AD plant. This effect resulted from its impact on the gross margin gap between AD-integrated farms and conventional beef farms, as detailed in Eq. (2). Thus, a ±20 % change in beef price led to a 1742 % variation in the 20-year NPV, fluctuating the profit needed for AD silage (as calculated in Eq. (2)) from €58/t DM to €164/t DM (Table S6). The substantial impact of AD silage on the overall NPV could be attributed to its influence on the AD plant's operating expenses, comprising 69 % of the total OPEX (Section 3.1.2). Similarly, Hosseini et al. [52] identified biomass pricing as a critical factor influencing the financial feasibility of biomethane production from agricultural feedstocks in southeastern Australia, highlighting that financial aids such as gate fees significantly impact the overall viability.

Variability in physical CAPEX and gas grid connection grants impacted the 20-year NPV by 93 % and 38 %, respectively. Their relatively lower impact compared to biomethane certificate and AD silage prices was mainly because these costs were incurred once (year 0), whereas biomethane certificate and silage prices influenced annual cash flows. These results emphasize the crucial role of the biomethane certificate and AD silage prices in determining the economic viability of anaerobic digestion and biomethane production systems. However, as previously mentioned, this study did not account for the potential commercialization of CO_2, which could serve as an additional revenue stream and enhance the financial feasibility of the AD system. The exclusion of CO_2 utilization represents a study limitation, as capturing and monetizing CO_2 from the biogas upgrading process could provide economic and environmental benefits. Additionally, potential environmental trade-offs associated with AD, such as the energy consumption and GHG emissions generated during silage production and transport, as well digestate management [8], should be carefully examined to adopt a more holistic approach in assessing the sustainability and economic viability of AD systems. Furthermore, in agricultural-based biogas systems, other farm parameters, like feedstock seasonality, can significantly affect AD plant performance and financial outcomes [16,53]. In this regard, modelling of the AD process can provide detailed insights into how variability in feedstock quantity and quality affect AD outputs, such as biomethane yield and digestate, over shorter periods (i.e., monthly) [54]. Combining models that capture seasonal variability of AD plant outputs with comprehensive AD-farm system models could offer an holistic approach to studying AD-farm system viability and requires further investigation.

4. Conclusions

This study examined the economic implications of integrating AD into livestock farming, focusing on the potential profitability and competitiveness of AD silage production compared to beef production. It also explored potential support schemes for successful operation of a 40 GWh biomethane plant co-digesting grass silage and cattle slurry. Results indicated that a price of €245/t DM (€61/t wet weight) is needed to attain a comparable gross margin as beef production. For the AD plant to fully cover this cost and remain profitable, a minimum biomethane price of €0.12/kWh is required, along with grants covering 20 % of physical CAPEX and 30 % of gas grid connection costs. At current biomethane prices (€0.098/kWh) and grants, the plant could only afford a silage price of €164/t DM, necessitating AD farm subsidies of €893/ha. These findings enhance our understanding of the economics of sustainable agricultural practices and bioenergy production. Future research should investigate intra-annual variability in AD plant operations, particularly how fluctuations in feedstock quality and quantity affect financial and sustainable performance.

CRediT authorship contribution statement

Sofia Tisocco: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **James J. Lenehan:** Writing – review & editing, Investigation, Conceptualization. **Xinmin Zhan:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Paul Crosson:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Notes

The authors declare no competing financial interest.

Acknowledgments

This research was financed by the Teagasc Walsh Scholarship Programme (Ref: 2021010). The inputs of Dr Stephen Nolan and Dr Ciara Beausang in the study concept and design are acknowledged.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2025.107702.

Data availability

Data will be made available on request.

References

[1] D. Gielen, F. Boshell, D. Saygin, M.D. Bazilian, N. Wagner, R. Gorini, The role of renewable energy in the global energy transformation, Energy Strategy Rev. 24 (2019) 38–50, https://doi.org/10.1016/j.esr.2019.01.006.

[2] IEA, Outlook for biogas and biomethane 2020. Prospects for organic growth. https://iea.blob.core.windows.net/assets/03aeb10c-c38c-4d10-bcecde92e9ab815f/Outlook_for_biogas_and_biomethane.pdf, 2020. (Accessed 29 May 2023).

[3] EBA, Biomethane in transport. https://www.europeanbiogas.eu/wp-content/uploads/2019/07/Biomethane-in-transport.pdf, 2016. (Accessed 29 May 2023).

[4] H. Bach, T. Mäkitie, T. Hansen, M. Steen, Blending new and old in sustainability transitions: technological alignment between fossil fuels and biofuels in Norwegian coastal shipping, Energy Res. Soc. Sci. 74 (2021) 101957, https://doi.org/10.1016/j.erss.2021.101957.

[5] S. Alberici, M. Moultak, J. Peters, The Future Role of Biomethane, Guidehouse, 2021. https://gasforclimate2050.eu/wp-content/uploads/2021/12/The_future_role_of_biomethane-December_2021.pdf. (Accessed 7 June 2023).
[6] T. Zhu, J. Curtis, M. Clancy, Promoting agricultural biogas and biomethane production: lessons from cross-country studies, Renew. Sustain. Energy Rev. 114 (2019) 109332, https://doi.org/10.1016/j.rser.2019.109332.
[7] NNFCC, A Detailed Economic Analysis of Anaerobic Digestion Technology and its Suitability to UK Farming and Waste Systems, second ed., 2010. https://www.nnfcc.co.uk/files/mydocs/Economic-Assessment-of-Anaerobic-Digestion-Technology-its-Suitability-to-UK-Farming-Waste-Systems-Report-NNFCC-10-010.pdf. (Accessed 10 January 2024).
[8] S. Tisocco, C. Beausang, X. Zhan, P. Crosson, Integration of anaerobic co-digestion of grass silage and cattle slurry within a livestock farming system in Ireland: quantification of greenhouse gas emission reduction and nutrient flow, Resour. Conserv. Recycl. 206 (2024) 107650, https://doi.org/10.1016/j.resconrec.2024.107650.
[9] Y. Zhang, Y. Jiang, S. Wang, Z. Wang, Y. Liu, Z. Hu, X. Zhan, Environmental sustainability assessment of pig manure mono- and co-digestion and dynamic land application of the digestate, Renew. Sustain. Energy Rev. 137 (2021), https://doi.org/10.1016/j.rser.2020.110476.
[10] E. Dillon, T. Donnellan, B. Moran, J. Lennon, Teagasc national farm survey 2022. https://www.teagasc.ie/media/website/publications/2023/NFS_prelim_results_2022.pdf, 2023. (Accessed 26 January 2024).
[11] C. Dennehy, P.G. Lawlor, G.E. Gardiner, Y. Jiang, L. Shalloo, X. Zhan, Stochastic modelling of the economic viability of on-farm co-digestion of pig manure and food waste in Ireland, Appl. Energy 205 (2017) 1528–1537, https://doi.org/10.1016/j.apenergy.2017.08.101.
[12] C. Geoghegan, C. O'Donoghue, An analysis of the social and private return to land use change from agriculture to renewable energy production in Ireland, J. Clean. Prod. 385 (2023) 135698, https://doi.org/10.1016/j.jclepro.2022.135698.
[13] 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, Bioprod. Biorefin. 13 (1) (2019) 129–139, https://doi.org/10.1002/bbb.1947.
[14] F. Ye, Z. Cai, Y.J. Chen, Y. Li, G. Hou, Subsidize farmers or bioenergy producer? The design of a government subsidy program for a bioenergy supply chain, Nav. Res. Logist. 68 (8) (2021) 1082–1097, https://doi.org/10.1002/nav.21909.
[15] C. Beausang, K. McDonnell, F. Murphy, Assessing the environmental sustainability of grass silage and cattle slurry for biogas production, J. Clean. Prod. 298 (2021) 126838, https://doi.org/10.1016/j.jclepro.2021.126838.
[16] D. Ó'Céileachair, R. O'Shea, J.D. Murphy, D.M. Wall, The effect of seasonal biomass availability and energy demand on the operation of an on-farm biomethane plant, J. Clean. Prod. 368 (2022) 133129, https://doi.org/10.1016/j.jclepro.2022.133129.
[17] CSO, Crops and livestock survey final results june 2022. https://www.cso.ie/en/releasesandpublications/ep/p-clsjf/cropsandlivestocksurveyfinalresultsjune2022/, 2022. (Accessed 25 January 2024).
[18] GNI, Biomethane energy report. https://www.gasnetworks.ie/docs/business/renewable-gas/biomethane-energy-report.pdf, 2023. (Accessed 18 December 2023).
[19] M. Kearney, E.G. O'Riordan, M. McGee, J. Breen, P. Crosson, Farm-level modelling of bioeconomic, greenhouse gas emissions and feed-food performance of pasture-based dairy-beef systems, Agric. Syst. 203 (2022) 103530, https://doi.org/10.1016/j.agsy.2022.103530.
[20] Bord Bia, Cattle price dashboards. https://www.bordbia.ie/farmers-growers/prices-markets/cattle-trade-prices/cattle-price-dashboard/, 2023. (Accessed 14 July 2023).
[21] E. Finneran, P. Crosson, P. O'Kiely, L. Shalloo, D. Forristal, M. Wallace, Simulation modelling of the cost of producing and utilising feeds for ruminants on Irish farms, J. Farm Manag. 14 (2) (2010) 95–116.
[22] P. Tidåker, C. Sundberg, I. Öborn, T. Kätterer, G. Bergkvist, Rotational grass/clover for biogas integrated with grain production–A life cycle perspective, Agric. Syst. 129 (2014) 133–141, https://doi.org/10.1016/j.agsy.2014.05.015.
[23] K. Rajendran, J.D. Browne, J.D. Murphy, What is the level of incentivisation required for biomethane upgrading technologies with carbon capture and reuse? Renew. Energy 133 (2019) 951–963, https://doi.org/10.1016/j.renene.2018.10.091.
[24] P. Kotek, A. Selei, B.T. Tóth, B. Felsmann, What can the EU do to address the high natural gas prices? Energy Policy 173 (2023) 113312 https://doi.org/10.1016/j.enpol.2022.113312.
[25] EBA, Biogenic CO_2 from the biogas industry. https://www.europeanbiogas.eu/wp-content/uploads/2022/10/Biogenic-CO2-from-the-biogas-industry_Sept2022-1.pdf, 2022. (Accessed 14 December 2023).
[26] S.S. Cordova, M. Gustafsson, M. Eklund, N. Svensson, What should we do with CO_2 from biogas upgrading? J. CO2 Util. 77 (2023) 102607 https://doi.org/10.1016/j.jcou.2023.102607.
[27] NORA, The renewable transport fuel obligation (formerly the biofuel obligation scheme), Guidance on: The Renewable Transport Fuel Obligation & applying for RTFO certificates and carbon savings & reporting and demonstrating compliance with the sustainability and GHG savings criteria (2023). https://www.nora.ie/rtfo. (Accessed 13 June 2023).
[28] European Commission, State aid: commission approves Italian scheme under Recovery and Resilience Facility to support biomethane production. https://ec.europa.eu/commission/presscorner/detail/en/IP_22_4803, 2022. (Accessed 16 August 2023).
[29] T. Hennessy, A. Kinsella, 40 years of Irish farming since joining the European union: a journey with the Teagasc national farm survey 1972 to 2012. https://www.teagasc.ie/media/website/publications/2013/NFS40years.pdf, 2013. (Accessed 16 December 2023).
[30] DAFM, Red clover silage measure. https://www.gov.ie/en/service/ae169-red-clover-silage-measure/, 2023. (Accessed 6 November 2023), 2023.
[31] D. Clavin, P. Crosson, J. Grant, P. O'Kiely, Red clover for silage: management impacts on herbage yield, nutritive value, ensilability and persistence, and relativity to perennial ryegrass, Grass Forage Sci. 72 (3) (2017) 414–431, https://doi.org/10.1111/gfs.12249.
[32] M. Lauer, J.K. Hansen, P. Lamers, D. Thrän, Making money from waste: the economic viability of producing biogas and biomethane in the Idaho dairy industry, Appl. Energy 222 (2018) 621–636, https://doi.org/10.1016/j.apenergy.2018.04.026.
[33] 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 13 (3) (2020) 637, https://doi.org/10.3390/en13030637.
[34] M.M.U.H. Khan, S. Jain, M. Vaezi, A. Kuma, Development of a decision model for the techno-economic assessment of municipal solid waste utilization pathways, Waste Manag. 48 (2016) 548–564, https://doi.org/10.1016/j.wasman.2015.10.016.
[35] M. O'Donovan, P. Dillon, P. Conaghan, D. Hennessy, Irish Grassland Research—main achievements and advancements in the past 60 yrs and where to progress to next, Irish J. Agric. Food Res. 61 (1) (2022) 1–11. https://www.jstor.org/stable/27225932.
[36] J. Freytag, W. Britz, T. Kuhn, The economic potential of organic production for stockless arable farms importing biogas digestate: a case study analysis for western Germany, Agric. Syst. 209 (2023) 103682, https://doi.org/10.1016/j.agsy.2023.103682.
[37] J.D. Huerta, A. Bose, D.M. Wall, J.D. Murphy, R. O'Shea, Assessing the cost variability of emissions abatement in small-scale on-farm anaerobic digestion, DeCarbon 1 (2023) 100008, https://doi.org/10.1016/j.decarb.2023.100008.
[38] R. O'Shea, D.M. Wall, I. Kilgallon, J.D. Browne, J.D. Murphy, Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region, Appl. Energy 188 (2017) 237–256, https://doi.org/10.1016/j.apenergy.2016.11.121.
[39] M.A. Eyl-Mazzega, C. Mathieu, K. Boesgaard, J. Daniel-Gromke, V. Denysenko, J. Liebetrau, S. Cornot-Gandolphe, Biogas and bio-methane in Europe: lessons from Denmark, Germany and Italy, mathieu_eyl-mazzega_biomethane_2019.pdf (ifri.org) (2019). (Accessed 22 January 2024).
[40] T. Sinigaglia, T.E. Freitag, A. Machado, V.B. Pedrozo, F.F. Rovai, R.T.G. Guilherme, T.D.M. Lanzanova, M. Dalla Nora, M.E.S. Martins, Current scenario and outlook for biogas and natural gas businesses in the mobility sector in Brazil, Int. J. Hydrog. Energy. 47 (24) (2022) 12074–12095, https://doi.org/10.1016/j.ijhydene.2022.01.234.
[41] L. Gil-Carrera, J.D. Browne, I. Kilgallon, J.D. Murphy, Feasibility study of an off-grid biomethane mobile solution for agri-waste, Appl. Energy 239 (2019) 471–481, https://doi.org/10.1016/j.apenergy.2019.01.141.
[42] R. Wahid, A.J. Ward, H.B. Møller, K. Søegaard, J. Eriksen, Biogas potential from forbs and grass-clover mixture with the application of near infrared spectroscopy, Bioresour. Technol. 198 (2015) 124–132, https://doi.org/10.1016/j.biortech.2015.08.154.
[43] A. Sobczak, E. Chomać-Pierzecka, A. Kokiel, M. Różycka, J. Stasiak, D. Soboń, Economic conditions of using biodegradable waste for biogas production, Using the Example of Poland and Germany, Energies 15 (14) (2022) 5239, https://doi.org/10.3390/en15145239.
[44] L. Shi, W.S. Simplicio, G. Wu, Z. Hu, H. Hu, X. Zhan, Nutrient recovery from digestate of anaerobic digestion of livestock manure: a review, Curr. Pollut. Rep. 4 (2018) 74–83, https://doi.org/10.1007/s40726-018-0082-z.
[45] T. Horschig, A. Welfle, E. Billig, D. Thrän, From Paris agreement to business cases for upgraded biogas: analysis of potential market uptake for biomethane plants in Germany using biogenic carbon capture and utilization technologies, Biomass Bioenergy 120 (2019) 313–323, https://doi.org/10.1016/j.biombioe.2018.11.022.
[46] H. Dai, N. Li, Y. Wang, X. Zhao, The analysis of three main investment criteria: NPV IRR and payback period, in: 7th Int. Conf. Financ. Innov. Econ. Dev. (ICFIED 2022), Atlantis Press, 2022, pp. 185–189, https://doi.org/10.2991/aebmr.k.220307.028.
[47] DECC, Climate action plan 2023. https://www.gov.ie/en/publication/7bd8c-climate-action-plan-2023/, 2023. (Accessed 17 January 2024).
[48] S. Carlos-Pinedo, Z. Wang, O. Eriksson, Methane yield from SS-AD: experiences to learn by a full spectrum analysis at laboratory-, pilot-and full-scale, Biomass Bioenergy 127 (2019) 105270, https://doi.org/10.1016/j.biombioe.2019.105270.
[49] Y. Li, Y. Han, Y. Zhang, W. Luo, G. Li, Anaerobic digestion of different agricultural wastes: a techno-economic assessment, Bioresour. Technol. 315 (2020) 123836, https://doi.org/10.1016/j.biortech.2020.123836.
[50] C. Hahn, A. Lüscher, S. Ernst-Hasler, M. Suter, A. Kahmen, Timing of drought in the growing season and strong legacy effects determine the annual productivity of temperate grasses in a changing climate, Biogeosci 18 (2) (2021) 585–604, https://doi.org/10.5194/bg-2020-100.
[51] R. Wheeler, M. Lobley, Managing extreme weather and climate change in UK agriculture: impacts, attitudes and action among farmers and stakeholders, Clim. Risk Manag. 32 (2021), https://doi.org/10.1016/j.crm.2021.100313, 1 00313.
[52] T. Hosseini, S.A. Culley, A. Zecchin, H.R. Maier, P.J. Ashman, Impact of co-digestion and degree of centralization on the yield and viability of biomethane

production: a case study in regional Australia, Energy Convers. Manag. X. 22 (2024) 100585, https://doi.org/10.1016/j.ecmx.2024.100585.
[53] S. O'Connor, E. Ehimen, S.C. Pillai, G. Lyons, C. Johnston, M. Wills, J. Bartlett, Decision support tool for the construction and seasonal operation of farm-scale anaerobic digestion plants, Results Eng 18 (2023) 101097, https://doi.org/10.1016/j.rineng.2023.101097.
[54] S. Tisocco, S. Weinrich, G. Lyons, M. Wills, X. Zhan, P. Crosson, Application of a simplified ADM1 for full-scale anaerobic co-digestion of cattle slurry and grass silage: assessment of input variability, Front. Environ. Sci. Eng. 18 (4) (2023) 50, https://doi.org/10.1007/s11783-024-1810-9.