Fuelling Change: The distributional and climate impacts of farmers supplying biomethane feedstocks in Ireland

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Fuelling Change: The distributional and climate impacts of farmers supplying biomethane feedstocks in Ireland

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Abstract

Farmers in the EU are the leading suppliers of feedstocks for biomethane production, a renewable energy source that can replace fossil gas in hard-to-abate sectors. However, the distributional impacts on farmers have not previously been explored. Understanding these helps ensure the EU's biomethane targets are met in a just way. In our case study of dairy and cattle farms in the Republic of Ireland, we investigated the distributional impacts of farms supplying grass silage and livestock slurry for biomethane production. Using microdata from the Irish National Farm Survey, we built a microsimulation model to estimate the impacts of different farms providing the biomethane feedstocks required to meet Ireland's national biomethane target. Our results show that low-income (largely cattle) farms stand to benefit economically from supplying biomethane feedstocks, decreasing inequality among farmers by 3.4%. However, since the farms switching away from livestock were low-intensity farms, this scenario also led to an intensification of overall livestock farming. In contrast, if the highest emitting farms switched to supplying biomethane feedstocks, they experienced a sizable drop in income, and a 2.0% increase in inequality. At the same time, this scenario saw the highest decrease in emissions at the lowest marginal abatement cost. Nevertheless, the marginal abatement cost remained above €400, higher than the estimated 2030 carbon shadow price for Ireland. These results demonstrate that agricultural biomethane feedstock cultivation can contribute to a just energy transition. However, it is a high-cost abatement option, and there is likely a trade-off between reducing inequality and other benefits.

Key words: Biomethane; Agriculture; Climate mitigation; Distributional impacts; Marginal abatement cost; Microsimulation; Ireland

JEL codes: Q12, Q42, Q18, Q52, Q54, C63

Abbreviations

AD	Anaerobic Digestion
CAPEX	Capital Expenditures
CEPCI	Chemical Engineering Plant Cost Index
CH4	Methane
CO_2e	Carbon dioxide equivalent
DM	Dry Matter
EU	European Union
FM	Fresh Matter
GHG	Greenhouse Gases
GWP-100	Global Warming Potential over a 100-year timeframe
IPCC	Intergovernmental Panel on Climate Change
ISSDA	Irish Social Science Data Archive
lu	livestock units
MAC	Marginal Abatement Cost
MJ	Megajoules
MWh	Megawatt hours
NFS	National Farm Survey
OPEX	Operating Expenditures
SEAI	Sustainable Energy Authority of Ireland
SMY	Specific Methane Yield
Teagasc	Agriculture and Food Development Authority of Ireland
TFE	True Fixed Effects
TRE	True Random Effects
TWh	Terrawatt hours
VS	Volatile Solids
RED	EU Renewable Energy Directive

1 Introduction

Biomethane is a renewable alternative to fossil gas and, as such, can help reduce gas imports while meeting the European Union's gas demand (Marconi and Rosa, 2023). Additionally, biomethane can contribute to the EU's climate targets by reducing emissions from energy, although estimates of the exact abatement potential vary widely (Vázquez-Rowe et al., 2014; Ardolino et al., 2018; Paolini et al., 2018; Lombardi and Francini, 2020; Gupta et al., 2022; Wu et al., 2023). Consequently, the European Union plans to scale up biomethane production to 35 billion cubic meters by 2030 (European Commission, 2022).

Past research has investigated the feasibility of establishing such a large-scale biomethane industry by analysing the availability of feedstocks and the economic case for biomethane production (see e.g., Cucchiella and D'Adamo, 2016; Mattioli et al., 2017; O'Shea et al., 2017; Chinnici et al., 2018; Chan Gutiérrez et al., 2018). However, implementation also hinges on feedstock controllers' willingness to provide them for biomethane production. This role primarily falls to farmers in Europe, as most biomethane is produced from crops and animal manure (IEA, 2020). Despite this, empirical evidence on the distributional impacts on farmers who supply biomethane feedstocks is very scant. Some research has been conducted on farmers' motivation to participate in the biomethane industry, although this has focused on farmers as energy producers (He et al., 2018; O'Connor et al., 2021). More closely related, Geoghegan and O'Donoghue (2023) analysed the private and social returns for farmers producing biomethane feedstocks, finding that when looking at average private returns by farm type, no farmers would have an incentive to switch from their current activity to biomethane feedstock production. However, incomes among farmers vary widely, and looking at farm microdata Geoghegan and O'Donoghue (2024) find that a small percentage of farms would benefit economically from cultivating grass silage for biomethane production. Their analysis identified the spatial dispersion of these farms but did not investigate the broader distributional implications for the farming sector.

In this article, we expand on this previous research by assessing the distributional impacts of some farmers' decisions to switch their operations to biomethane feedstock provision. Using a microsimulation model, we investigate a range of scenarios, selecting which farms will switch their operations based on farm profitability, as in previous studies (Geoghegan and O'Donoghue, 2023, 2024), and consider other criteria, such as farm technical efficiency and the potential for emissions savings. Additionally, we use the details in farm microdata to understand which types of farms switch under different scenarios. This will not only help direct policy development but is also important due to emergent concerns that linking biomethane production and agriculture may lead to environmentally and socially harmful intensification of land use (Magnolo et al., 2024). Finally, we quantify the climate impacts of each scenario to ensure the distributional implications are put into the broader context of the main benefit of biomethane production.

Our research focuses on the Republic of Ireland as a case study region in the EU with a large pasture-based farming system. The government has set a target of 5.7 TWh of annual biomethane production by 2030. Additionally, due to the large number of livestock, Ireland needs to reduce emissions from agriculture to comply with EU climate targets (Government of Ireland, 2015, 2022b), with agricultural emissions currently contributing 37.8% to Ireland's overall emissions (Environmental Protection Agency, n. d.). Nevertheless, the biomethane industry in Ireland is presently limited, making an ex-ante analysis of possible impacts a timely contribution.

The article is structured as follows: We provide some background information on the Irish policy landscape and the co-digestion of grass silage and animal slurries for biomethane production in section 2. In section 3, we present the data we used and our methods. First, we introduce the National Farm Survey data (3.1). Next, we outline the different scenarios we analysed (3.2.1) and provide an overview of the selection criteria and process we applied to select biomethane candidate farms (3.2.2). Finally, we describe our microsimulation model's different steps and assumptions (3.2.3). In section 4, we first present the results of our biomethane farm selection, including the characteristics of selected farms under the different scenarios (4.1). We then highlight the energy produced under each scenario (4.2), the associated costs (4.3), the distributional impacts (4.4), the abatement potential (4.5), and the marginal abatement cost (4.6). Finally, in section 5, we discuss our results and conclude.

2 Background

In its 2023 Climate Action Plan, the Irish government set out a goal of 5.7 TWh biomethane production by 2030 (Government of Ireland, 2023, p. 219). This target was put forward as one of the steps to deliver emissions reductions from agriculture and was firmly grounded in the potential of agricultural feedstocks. The National Biomethane Strategy was published one year later, outlining the Irish government's approach to achieving the target. In the foreword to the strategy, the Minister for Agriculture, Food and the Marine describes it as "first and foremost an agri-centric strategy", identifying farmers as the central stakeholders without whom "the industry will not develop at the required scale" (DAFM and DECC, 2024, p. 1).

Research underscores the importance of agricultural feedstock, particularly grass silage, in achieving Ireland's biomethane target. Organic wastes are often considered the first choice for biomethane feedstocks, as their use can help close the circular economy loop (IEA Bioenergy, 2018). However, the total amount of non-agricultural waste in Ireland is likely to produce a maximum of around 1 TWh of biomethane[1] (Environmental Protection Agency Ireland (EPA) et al., 2011; Murphy et al., 2013; O'Shea et al., 2016; Allen et al., 2016; Sustainable Energy Authority of Ireland (SEAI), 2017a; Dowd et al., 2022; SEAI, 2022). On the other hand, the agricultural sector can provide both animal manure and grass silage, which have been estimated to theoretically provide enough energy to reach the 5.7 TWh target on their own. However, the practical potential may fall short of this estimate (O'Shea et al., 2017; Sustainable Energy Authority of Ireland (SEAI), 2017a; Ó Céileachair et al., 2021). Grass silage, in particular, has been the focus of much attention as grassland makes up about 82% of agricultural land in the Republic of Ireland (CSO, 2022) and has a high energy content (Wall et al., 2013).

However, to fulfill the requirements for renewable energy set out in the EU's recast Renewable Energy Directive (RED) (European Parliament and Council of the European Union, 2018), grass silage has to be co-digested with slurry or fall short of the required emissions reductions (Beausang et al., 2021). The exact ratio at which grass silage and animal slurry need to be co-digested to fulfill the RED requirements is unclear. While higher slurry percentages are beneficial for emissions reductions, higher grass silage percentages are more economically viable due to their higher energy content. However, at least a small percentage of slurry is beneficial in supplying essential nutrients (Wall et al., 2013). Different ratios have been evaluated in past research. Research in Ireland shows that at least 50% slurry, and likely more, on a fresh weight basis, would be required to meet the RED target for transport and heat (SEAI, 2022; Bose et al., 2022a; Wu et al., 2023). Beausang et al. (2021) evaluate the impact of biomethane production on multiple environmental indicators and find that at 40% slurry on a volatile solids (VS) basis, which is equivalent to significantly more than 50% of slurry fresh matter, all three environmental categories the authors assess experience a net improvement.

[1] And this value includes slaughterhouse and milk processing waste, which are closely linked to livestock farming.

3 Data & methods

3.1 Data

The dataset we used is the Teagasc National Farm Survey (2000 – 2017) as accessed through the Irish Social Science Data Archive (ISSDA). The National Farm Survey (NFS) is a representative sample of Ireland's farming population, including detailed panel data on financial variables. It is collected yearly by the Agriculture and Food Development Authority of Ireland (Teagasc). Our analysis focuses on dairy and beef farms. Together, these farms represent almost 70% of Irish farms, with more than half (56.1%) specialising in beef production, compared to only 11.4% specialist dairy farms in 2023 CSO (2024). However, dairy farming is more economically significant, with an income of €1,557 per hectare in 2024. In contrast, cattle farming has a much lower income of €432 per hectare and is heavily dependent on subsidies (Teagasc, 2025). Additionally, policy measures to reduce agricultural emissions will likely target these two sectors.

The entire panel dataset from 2000 - 2017 was used for a stochastic frontier analysis to obtain the farm-level technical efficiency estimates. The microsimulation model, on the other hand, was built using only cross-sectional data from 2017, as the model required each farm to be represented only once, and since 2017 is the most recent sample in the dataset. The 2017 data is scaled up using the weights provided in the NFS so that the outputs represent the whole specialised dairy and cattle farming population. All references to data for anything other than the stochastic frontier analysis refer to values scaled to the population level. An overview of the summary statistics for this scaled 2017 subset of the NFS data is given in Table 3.1. The summary statistics for the panel dataset (unweighted and unscaled) are in the appendix.

Table 3.1: Summary statistics - National Farm Survey data, 2017, weighted

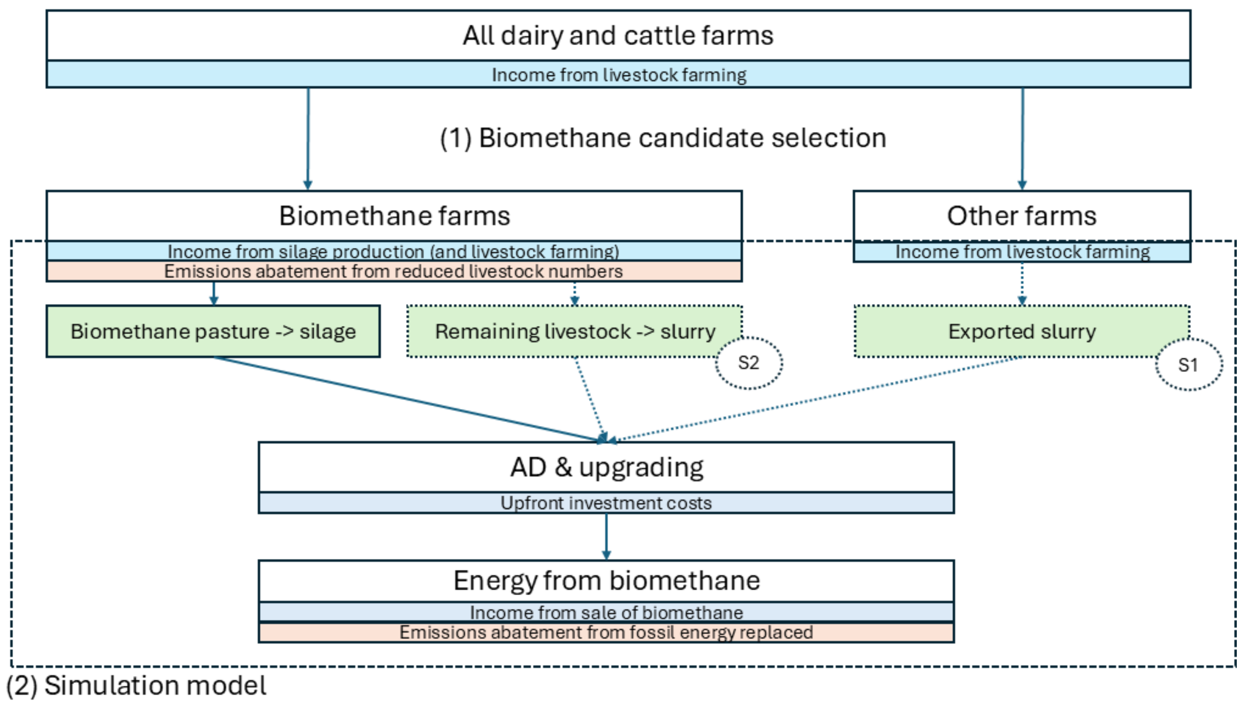
	Cattle	Dairy	Total
N	37,867 (71.4%)	15,175 (28.6%)	53,041 (100.0%)
Average land farmed (ha)	35 (20)	56 (29)	41 (25)
Civil status of main farmer			
Single	12,156 (32.1%)	2,527 (16.7%)	14,682 (27.7%)
Married	25,711 (67.9%)	12,648 (83.3%)	38,359 (72.3%)
Gender of main farmer			
Man	36,015 (95.1%)	14,913 (98.3%)	50,928 (96.0%)
Woman	1,852 (4.9%)	262 (1.7%)	2,113 (4.0%)
Age of main farmer	59 (12)	53 (10)	57 (12)
Average farm family income (€/a)	14,129 (15,480)	84,291 (54,788)	34,202 (45,113)
Average livestock units	45 (30)	113 (62)	64 (52)
Pasture area %	93 (13)	96 (9)	94 (12)
Stocking rate (lu/ha)	1.4 (.52)	2.2 (.55)	1.6 (.62)
High environmental subsidies			
No	24,196 (63.9%)	13,412 (88.4%)	37,608 (70.9%)
Yes	13,671 (36.1%)	1,763 (11.6%)	15,434 (29.1%)

Note: All variables are weighted / scaled up to population level according to the population weights provided in the National Farm Survey. For continuous variables, the mean is displayed with the standard deviation shown in brackets. For factor variables, the frequency is shown with the percentage in brackets.

3.2 Methods

Figure 1 provides an overview of the steps in our analysis. The first step is selecting biomethane candidates from the dairy and cattle farms in our sample. This selection involved different criteria for each scenario. In a second step, we developed a microsimulation model to calculate the feedstocks produced by the various farms (green) and the resulting energy potential, as well as changes in income for the biomethane farms (blue), energy production costs (dark blue), and emissions abated at different steps in the process (orange).

Figure 1: Graphical representation of farm selection and simulation model



*Note: S1 and S2 refer to scenarios 1 and 2, where scenario 1 involves farmers switching their entire operations, and scenario 2 involves farmers converting only a portion of their farmland to biomethane silage.

3.2.1 Scenarios

We analysed four sub-scenarios grouped under two overarching scenarios. For an overview, see Table 3.2.

The two overarching scenarios differ in whether farms switch all or only part of their pasture to the cultivation of grass silage for biomethane production (hereafter, 'biomethane silage'). Scenario 1 involves possible candidates for biomethane production (subsequently referred to as 'biomethane candidates') fully converting their farms to biomethane silage production, reducing their herd to zero, whereas in scenario 2 biomethane candidates only convert a portion of their farm that is of sufficient size to produce enough silage to match their slurry output at a 3:2 ratio. As a result, farms in Scenario 2 do not need to rely on external inputs to achieve the desired feedstock composition for anaerobic digestion (AD), the first step in the biomethane production process. This scenario aligns with the idea of farms forming cooperatives to produce energy from

	Scenario 1: Total conversion			Scenario 2: Partial conversion
	(a) Efficiency	(b) Profit	(c) Climate	Partial
Pasture use				
Silage only	✓	✓	✓	
Silage and livestock				✓
Biomethane candidate criteria				
Good soil	✓	✓	✓	✓
Low efficiency	✓			
Low profit margin		✓		
GHG emissions			✓	

Table 3.2: Scenario descriptions

joint AD plants they self-supply. It avoids spatial issues where not enough slurry is available within the desired radius to complement the produced silage, which is likely to be a problem in scenario 1.

AD plants are assumed to operate for 8,585 hours per year, corresponding to an availability rate of 98% and near-continuous operation throughout the year. This assumption follows Padi et al. (2023). Grass feedstock is assumed to be purchased and transported as silage rather than fresh grass. This reflects standard agricultural practice, whereby harvested grass is typically conserved as silage to facilitate storage while maintaining its nutritional value (FAO, 2002).

Within these scenarios, we examine sub-scenarios to illustrate the implications of different farm types adopting, or being encouraged to adopt, biomethane silage production to reach the government target of 5.7 TWh of biomethane by 2030 (Government of Ireland, 2024). In so doing, we examine the potential outcomes of policies chosen to support different objectives, based on efficiency, economic or environmental criteria. Specifically, focusing on low efficiency farms to contribute to biomethane silage production could increase farm efficiency. Prioritising farm incomes would lead to a focus on encouraging farmers who stand to gain the most economically to adopt biomethane silage. Finally, a climate focus would prioritise adoption patterns that are most effective at reducing greenhouse gas emissions.

The sub-scenarios, therefore, differ based on the selection process used to determine which farms switch to the cultivation of biomethane silage. For all sub-scenarios, only those farms with sufficiently good soil to grow grass silage are considered as biomethane candidates. In addition to this mandatory requirement, each sub-scenario included one further criterion to select biomethane candidates. These were: (1a) farms with the lowest farm-level technical efficiency estimate (calculated as described in section 3.2.2); (1b) farms with the lowest per hectare profit margin from livestock; and (1c) farms with the highest per hectare greenhouse gas emissions.

For the ‘partial’ Scenario, there are no subscenarios. This is because to meet the policy target of 5.7TWh of biomethane, all farms with good soil were needed to contribute, provided that each farm’s conversion from pasture to biomethane silage was partial only. As such, scenario 2 gives insight into the likely situation of farmers not converting their entire farms to biomethane silage production.

Rather than converting pasture to biomethane silage, farmers could increase pasture productivity to provide grass silage while maintaining grazing on all their land. However, we assumed that land would be set aside for the cultivation of biomethane silage by reducing herd size for several reasons. First, the suckler herd has been declining for nearly the past decade (Teagasc, 2024) and projections see this decline continuing (SEAI, 2022, pp. 46-48), which would be in line with a reduction in the herd to provide space for biomethane silage. Second, the dairy herd is projected to increase, as a result of which any productivity increases are expected to be absorbed by the increasing herd sizes (SEAI, 2022, pp. 46-48). Therefore, dairy farmers would have to deliberately reduce their herd size beyond these projections and set aside land for biomethane silage production. Additionally, intensification of pasture-based systems generally increases environmental pressures (Chobtang et al., 2017), thereby reducing any benefits from biomethane production. Adopting a strategy of herd size reduction rather than pasture intensification avoids these adverse impacts, which this model could not adequately represent.

3.2.2 Biomethane farm selection

Selection criteria

Soil quality. Among the six soil classes, only farms classified as Classes 1 to 3 were included in the analysis. The other soil classes were excluded because they are considered to have limited to minimal agricultural use due to poor drainage and high altitude.

Efficiency. We use Stochastic Frontier Analysis (SFA) to estimate technical efficiency at the farm level and examine how farm characteristics affect it. The following production function can represent the production technology of farms:

$$\ln Y_{it} = f(\ln X_{it}, t) + v_{it} - u_{it} \tag{1}$$

Here, Y_{it} is the farm output, $\mathbf{X_{it}}$ is the vector of inputs, i is an index for the farm, and t is an index for the year. The production function includes a time trend t to account for technological changes. A feature of SFA is that the production function includes two error terms: an inefficiency term u_{it} and a stochastic random error v_{it} (Meeusen and van Den Broeck, 1977; Aigner et al., 1977; Kumbhakar et al., 2014). The full estimation approach we followed is presented in the appendix, along with the estimation results.

Profit margin. Each farm's per-hectare profit margin from livestock was calculated by dividing the total livestock gross margin by the hectares of pasture. This measure was used as it represents the opportunity cost of switching to grass silage production for biomethane on any given hectare of pasture.

Greenhouse gas emissions. For the emissions associated with livestock farming, we used the emissions factors from Ireland's National Inventory Report 2019 (Duffy et al., 2019). The report provides data on enteric fermentation according to animal type, which we merged with the farm microdata to determine individual emissions by farm based on herd composition[2]. Per-hectare CO_2 equivalent emissions from livestock

[2]Methane emissions were converted to CO_2 equivalents using the global warming potential of methane over 100 years (GWP-100), taken from the IPCC's 6th Assessment Report (Intergovernmental Panel On Climate Change, 2021, Table 7,.15)

were calculated by dividing farm livestock emissions by pasture area to determine each farm's emissions intensity.

Selection process

Depending on the scenario, all farms with good soil were sorted by efficiency (from low to high), profit margin (low to high), or GHG emissions (high to low). They were then separated by farm type (dairy and cattle). Each farm type was allocated a share of the government biomethane target (5.7 TWh) corresponding to its share of total pastureland in our sample, representing each farm type's theoretical energy potential. This was 60.38% for cattle farms and 39.62% for dairy farms. Starting at the top of the list for each farm type, farms were selected as biomethane candidates one by one until each farm type's energy reached or exceeded its share of the 5.7 TWh biomethane target. Together, the farms selected from both farm types were guaranteed to meet the government target. The profit scenario was an exception. Here, farms were only chosen if they were identified as economically viable candidates for switching (outlined above). Since this was true of only a few dairy farms in the sample, the remaining energy gap was filled by selecting additional cattle farms.

3.2.3 Microsimulation model

All model assumptions are summarized in table 3.3.

Biomethane farms and production

Total silage production on each farm is calculated based on the number of hectares set aside for silage production and the silage dry matter yield per ha taken from Moloney et al. (2021) (see table 3.3). The 11 tDM/ha reflects the lower bound for mixed-species swards with low to no inorganic nitrogen treatment. The fresh matter yield is extrapolated from there, assuming 25% dry matter as in SEAI (2022, pp. 51-55) and the volatile solids ratio is taken from Tisocco et al. (2024).

For scenario 1, slurry has to be imported from other farms at a 3:2 silage:slurry VS ratio. For scenario 2, the on-farm slurry yield is calculated. Slurry yield is based on the EU Regulations on Good Agricultural Practice for the Protection of Waters (Government of Ireland, 2022a, see table 1.3), which details slurry storage requirements per livestock unit. Since the value reflects a storage requirement rather than actual slurry production, it is likely an upper bound. Cattle are assumed to be housed indoors 16 weeks of the year (Tisocco et al., 2024) with no slurry during pasture grazing. Dry matter and volatile solids percentages are taken from Tisocco et al. (2024).

The total energy yield for each of the respective scenarios was then determined using the values in SEAI (2022, pp. 51-55) for silage and Tisocco et al. (2024) for slurry (see table 3.3).

Costs of biomethane production

We then estimated the technological production costs of biomethane. Capital expenditure (CAPEX) includes the costs of building the anaerobic digesters and the biomethane upgrading facilities. We assume that biomethane will be delivered to the end user or the gas grid via a virtual pipeline (delivery by trucks), as direct gas grid connections would only be viable for very large producers.

Table 3.3: Model assumptions

Parameters	Values	Units	References
Feedstock variables			
Silage price	47	€/tFM	SEAI 2022, pp. 51-55
Silage production cost	37	€/tFM	SEAI 2022, pp. 51-55
Silage fresh matter yield	44	tFM/ha	Adapted from DM yield in Moloney et al. 2021 assuming 25% DM as in SEAI 2022, pp. 51-55
Silage dry matter yield	11	tDM/ha	Moloney et al. 2021
Volatile solids ratio silage	92.0	% of DM	Tisocco et al. 2024
Energy from silage	3.09	MWh/tDM	SEAI 2022, pp. 51-55
Slurry fresh matter yield	0.33	m^3/lu/week	Government of Ireland 2022a, Schedule 2, Table 2
Slurry dry matter yield	6.3	% of FM	Tisocco et al. 2024
Volatile solids ratio slurry	77.6	% of DM	Tisocco et al. 2024
Energy from slurry	186	m^3CH_4/tVS	Tisocco et al. 2024
Biomethane production variables			
AD plant size	75	ktFM/a	Padi et al. 2023
Upgrading plant operating time	8585	h/a	Padi et al. 2023
Biomethane price	47.52	€/MWh	Fossil gas price from Trading Economics, accessed on September 5th, 2024, combined with Natural Gas Carbon Tax from Revenue 2025
Emissions variables			
Global warming potential of methane	27	tCO_2e/tCH_4	Intergovernmental Panel On Climate Change 2021, Table 7.15; using GWP-100
Energy emissions savings, heat	0.2361	tCO_2e/MWh	Assuming REDII conditions for heat are met as in Long and Murphy 2019, Table 5
Energy emissions savings, transport	0.2865	tCO_2e/MWh	Assuming REDII conditions for heat are met as in Long and Murphy 2019, Table 5
Carbon shadow price	408	€/tCO_2e	Kevany and Foley 2024, for the year 2030
Discount rate (costs)	0.1025		Padi et al. 2023
Discount rate (emissions)	0.04		Wu et al. 2023

Note: These are the values used in the microsimulation model.

To determine the cost of anaerobic digestion (AD) plants, we first calculated the number required. This was done by adding the total tons of silage fresh matter and cubic meters of slurry, then dividing by 7500. At 75 kt FM intake per year, the anaerobic digestion plants in our model represent medium-sized anaerobic digesters according to Padi et al. (2023). Each AD plant is assumed to be coupled with a biogas upgrading plant.

The CAPEX calculation for all AD and upgrading plants was adapted from Padi et al. (2023) and adjusted for current inflation levels. The equations are in the appendix. The costs for the virtual pipeline are taken from Czyrnek-Delêtre et al. (2016), with two trucks and one compressor allocated to each upgrading plant.

The operating expenditure (OPEX) was taken directly from the Slieveardagh plant modelled by Padi et al. (2023). This plant was chosen because it was the closest to the plants modelled here, with a 71.25 kt/a feedstock throughput and a silage slurry ratio of 4:1. The value used was a specific OPEX of 52.35 €/t feedstock, which is the average for feedstock costs between €35 and €56. The specific OPEX was then multiplied by the total amount of feedstock (silage and slurry).

Finally, the revenue from the produced biomethane is subtracted from the costs. We assume here that biomethane producers will be able to sell biomethane at the price of fossil gas (€36.04/MWh; Trading Economics) plus the cost of the Natural Gas Carbon Tax (€11.48/MWh; Revenue, 2025), from which biomethane would be exempt (see table 3.3).

Distributional impacts for farmers

SEAI estimates for grass silage price and production costs were used to calculate the gross margin from biomethane silage (SEAI, 2022, ; see Table 3.3). The values were based on the assumption that silage is grown on land released due to a smaller herd size, reflecting the scenarios investigated here. The income from biomethane silage for a given biomethane farm was calculated by multiplying this gross margin by the silage area:

$$\text{Silage Income}_{bio} = (\text{Silage Gross Margin} \times \text{Silage Area}) \tag{2}$$

Where *silage gross margin* is a per ha value.

In scenario 2, farms maintained some of their livestock. Therefore, they continued to receive an income from the remaining livestock. This was calculated by multiplying the per ha gross margin for livestock by the area remaining after deducting the area set aside for biomethane silage cultivation:

$$\text{Livestock Income}_{bio} = \text{Livestock Gross Margin} \times (\text{Total Pasture Area} - \text{Silage Area}) \tag{3}$$

where *livestock gross margin* is a per ha value.

The new biomethane-based farm income was then calculated as follows, by subtracting the total income from livestock from the original income and then adding the new income from silage and, for scenario 2, the income from the remaining livestock:

$$\text{Farm Income}_{bio} = \text{Original Income} - \text{Total Livestock Gross Margin} + \text{Silage Income}_{bio} + \text{Livestock Income}_{bio} \tag{4}$$

where *total livestock gross margin* is for the whole farm and *original income* is the income before the intervention.

To estimate the distributional impact of the different scenarios, the Gini index is calculated both before and after the change in income. Income from off-farm work was not included in the NFS dataset and could not be accounted for.

Emissions reductions

Two types of emissions reductions were calculated. The first is termed 'livestock abatement' and refers to the emissions savings associated with a decrease in the livestock herd. For scenario 1, the total livestock emissions associated with the selected biomethane farms are considered abated. In scenario 2, the livestock herd is reduced by the same percentage as pasture is converted to biomethane silage, so the abatement is equivalent to that percentage of the total livestock emissions.

The second component of the emissions reductions is termed 'energy abatement'. These are the emissions reductions which arise from replacing fossil fuels with biomethane. The exact emissions reductions achieved from this are highly debated and depend on several factors, such as end use, silage-to-slurry ratio, technology, methane losses, and accounting conventions (which emissions reductions are allocated to which end products). For this study, we assume that the requirements set out in the recast Renewable Energy Directive are met. This assumption is plausible but optimistic with the literature presenting a mixed picture, especially on meeting reduction requirements for end use as heat (Ó Céileachair et al., 2022; O'Shea et al., 2017; Wu et al., 2023; Bose et al., 2022a; Climate Change Advisory Council Ireland, 2023; Sustainable Energy Authority of Ireland (SEAI), 2017b). To determine the emissions savings we follow Long and Murphy (2019), who calculate the maximum permitted emissions based on the requirements set out in the recast RED. The values differ depending on the end use of biomethane for heat and for transport, as biomethane replaces fossil gas and diesel, respectively, as well as different requirements set out in the RED according to end use. The authors identify values of 14.4 gCO_2e/MJ for heat and 32.9 gCO_2e/MJ for transport. We assume that biomethane producers will produce for all possible end uses and, therefore, adhere to the stricter requirements for use as heat. We then calculate the difference between 14.4 gCO_2e/MJ and the fossil fuel comparators for heat and for transport (Long and Murphy, 2019, Table 5) to identify the emissions reductions achieved for each end use (see table 3.3 for resulting values).

Marginal abatement cost

To determine the marginal abatement cost, we first calculated the net present value (NPV) of the biomethane production plants. Since our analysis considers biomethane production not from the standpoint of a biomethane producer but from a broader societal perspective, we have included the income gains and losses of farmers in the traditional NPV calculation as shown in equation (7), which is loosely adapted from Padi et al. (2023). Nevertheless, to facilitate the calculation, we selected a 20-year time period, which is the expected lifetime of a biomethane plant.

$$\text{NPV} = \left[\sum_{t=0}^{20} \frac{\text{Revenue}_t - \text{OPEX}_t + \text{Net Farm Income Changes}_t}{(1 + \text{Discount Rate})^t} \right] - (\text{CAPEX}_{total} \times 1.05) \quad (5)$$

Revenue is the income from the produced biomethane; *net farm income changes* are the netted income gains and losses from farmers' switch to biomethane feedstock production; $CAPEX_{total}$ refers to the combined CAPEX from AD and upgrading and is multiplied by 1.05 to include working capital (see Padi et al., 2023).

The marginal abatement cost was then calculated by dividing the negative NPV by the discounted carbon abatement as in equation (6), based on (Bose et al., 2022a).

$$\text{MAC} = \frac{-NPV}{\sum_{t=0}^{N} \frac{CO_2\text{Abatement}_t}{(1+\text{Discount rate})^t}} \tag{6}$$

3.2.4 Sensitivity analysis

Several of the parameters in our model are subject to uncertainty, and there is substantial variation in the literature regarding what values are used. Consequently, we conducted a sensitivity analysis across a range of parameters we perceived as most variable. For each parameter, we have a "low" and a "high" scenario, with all values outlined in Table 5.3 in Appendix V. The only exception is the carbon shadow price, where the shadow price recommended by the Irish government is already high, so we have only included a low scenario. For each parameter, the distance between the high and low scenarios and the original value is not necessarily the same; instead, they represent the outer bounds within which the parameter's value might fluctuate.

4 Results

4.1 Biomethane candidate characteristics

When examining the characteristics of the selected biomethane farms (see Table 4.2), the partial scenario largely reflects those of the population as a whole (see Table 3.1) due to the high percentage of farms selected. Consequently, the discussion focuses primarily on the three full-conversion sub-scenarios, which exhibit more distinct characteristics.

The proportion of cattle and dairy farms varies substantially between the sub-scenarios. In the efficiency and climate scenarios, cattle farms account for 68.6% and 75.8% of biomethane candidates, respectively. The profit scenario is a notable outlier, with cattle farms comprising 98.4% of selected farms and dairy farms only 1.6%. This reflects the additional requirement that a switch to biomethane silage production must also be economically beneficial, a condition that was met by relatively few dairy farms.

The climate scenario is characterised by substantially smaller farms, with an average farm size of 27 ha compared with 34 ha in the efficiency scenario and 39 ha in the profit scenario. The smaller average farm size also explains why a larger number of farms (4,058) are required to meet the biomethane target under this scenario.

Table 4.1: Biomethane farm summary statistics

	Efficiency	Profit	Climate	Partial
Biomethane farms	3,280	3,058	4,058	38,083
Average land farmed (ha)	34 (15)	39 (18)	27 (20)	41 (25)
Civil status of main farmer				
Single	1,175 (35.8%)	1,528 (50.0%)	498 (12.3%)	9,919 (26.0%)
Married	2,105 (64.2%)	1,530 (50.0%)	3,560 (87.7%)	28,164 (74.0%)
Gender of main farmer				
Man	2,931 (89.4%)	2,686 (87.8%)	3,987 (98.2%)	36,607 (96.1%)
Woman	348 (10.6%)	372 (12.2%)	72 (1.8%)	1,476 (3.9%)
Age farmer	59 (13)	61 (14)	57 (12)	57 (12)
Farm type				
Cattle	2,250 (68.6%)	3,010 (98.4%)	3,077 (75.8%)	26,525 (69.7%)
Dairy	1,030 (31.4%)	48 (1.6%)	981 (24.2%)	11,558 (30.3%)
Average farm family income (€/a)	11,984 (18,386)	5,431 (7,689)	34,761 (50,772)	38,003 (47,949)
Average livestock units	43 (31)	36 (20)	73 (63)	68 (54)
Pasture area (%)	94 (13)	91 (12)	100 (1.7)	95 (10)
Stocking rate	1.3 (.59)	1.1 (.41)	2.5 (.53)	1.7 (.62)
High environmental subsidy				
No	2,184 (66.6%)	1,588 (51.9%)	3,674 (90.5%)	26,952 (70.8%)
Yes	1,095 (33.4%)	1,470 (48.1%)	385 (9.5%)	11,132 (29.2%)

Note: All variables are weighted / scaled up to population level according to the population weights provided in the National Farm Survey. For continuous variables, the mean is displayed with the standard deviation shown in brackets. For factor variables, the frequency is shown with the percentage in brackets.

Livestock intensity differs considerably across scenarios. The profit scenario has the lowest average stocking rate at 1.1 livestock units per hectare, despite being dominated by cattle farms. By contrast, the climate scenario has the highest average stocking rate at 2.5 livestock units per hectare, around 50% higher than the average of the partial scenario (1.7 LU/ha). Consistent with this pattern, farms selected under the climate scenario also have the highest average livestock numbers (73 LU), while those in the profit scenario have the lowest (36 LU).

Farm income also varies markedly. The profit scenario contains farms with the lowest average family income (€5,431 per year), substantially below the averages observed in the efficiency (€11,984) and climate (€34,761) scenarios. In contrast, the climate scenario selects farms with income levels that are close to the overall farming population average.

Several other farm characteristics also differ across scenarios. The share of farms receiving high environmental subsidies is highest in the profit scenario (48.1%) and lowest in the climate scenario (9.5%). Similarly, the proportion of women farmers ranges from 12.2% in the profit scenario to only 1.8% in the climate scenario. While these characteristics vary substantially across scenarios, the most pronounced differences are observed in farm type, income, livestock intensity, and farm size.

Although income varied drastically between scenarios, it only significantly affected the odds of being selected as biomethane candidate for the profit scenario. In this scenario, being in the bottom 40% of earners increased

Table 4.2: Biomethane farm summary statistics

	Efficiency	Profit	Climate	Partial
Biomethane farms	3,280	3,058	4,058	38,083
Average land farmed (ha)	34 (15)	39 (18)	27 (20)	41 (25)
Civil status of main farmer				
Single	1,175 (35.8%)	1,528 (50.0%)	498 (12.3%)	9,919 (26.0%)
Married	2,105 (64.2%)	1,530 (50.0%)	3,560 (87.7%)	28,164 (74.0%)
Gender of main farmer				
Man	2,931 (89.4%)	2,686 (87.8%)	3,987 (98.2%)	36,607 (96.1%)
Woman	348 (10.6%)	372 (12.2%)	72 (1.8%)	1,476 (3.9%)
Age farmer	59 (13)	61 (14)	57 (12)	57 (12)
Farm type				
Cattle	2,250 (68.6%)	3,010 (98.4%)	3,077 (75.8%)	26,525 (69.7%)
Dairy	1,030 (31.4%)	48 (1.6%)	981 (24.2%)	11,558 (30.3%)
Average farm family income (€/a)	11,984 (18,386)	5,431 (7,689)	34,761 (50,772)	38,003 (47,949)
Average livestock units	43 (31)	36 (20)	73 (63)	68 (54)
Pasture area (%)	94 (13)	91 (12)	100 (1.7)	95 (10)
Stocking rate	1.3 (.59)	1.1 (.41)	2.5 (.53)	1.7 (.62)
High environmental subsidy				
No	2,184 (66.6%)	1,588 (51.9%)	3,674 (90.5%)	26,952 (70.8%)
Yes	1,095 (33.4%)	1,470 (48.1%)	385 (9.5%)	11,132 (29.2%)

Note: All variables are weighted / scaled up to population level according to the population weights provided in the National Farm Survey. For continuous variables, the mean is displayed with the standard deviation shown in brackets. For factor variables, the frequency is shown with the percentage in brackets.

the selection odds by a factor of 6.9. This was reflected in the average income, which was only €5,431. In contrast, the population average is €34,202.

The other variables included in the regression were largely not statistically significant. Despite this, there was substantial variation between scenarios for some of these variables. For example, the percentage of farms receiving high environmental subsidies was highest in the profit scenario at 48.1% and lowest in the climate scenario at 9.5%. Similarly, the percentage of women farmers was 12.2% in the profit scenario and 1.8% in the climate scenario.

4.2 Energy produced and inputs to energy production

Our results show that between 5 and 8% of cattle and dairy farms would need to exclusively produce grass silage for biomethane production to meet government targets (see Table 4.3). If each farm completely self-supplied slurry and silage while only slightly reducing their herd size, 71.8% of farms, or all farms with good soil, would need to participate, and even then this scenario would only reach around 4.4 TWh. In the three other scenarios, reaching the biomethane target requires just over 100 kha of pasture dedicated to biomethane silage but also relies on the import of around 17 million m^3 of slurry from non-selected farms. In the partial scenario, the provision of slurry is guaranteed and not reliant on imports from non-participating farms. With 71.8% of the farming population participating, the amount of slurry produced in Scenario 2 only reaches just under 13 million m^3, casting doubt on farms being able to supply the 17 million m^3 required for the total conversion scenarios. This indicates that at a 3:2 silage:slurry ratio it may not be possible to reach the government target of 5.7 TWh biomethane from on-farm feedstocks alone.

Table 4.3: Biomethane farms and production by scenario

Scenario 1: Total conversion	**Efficiency**	**Profit**	**Climate**
Number of biomethane farms (% out of total farms)	3,280 (6.2%)	3,058 (5.8%)	4,058 (7.7%)
Pasture dedicated to biomethane (kha)	104.20	106.84	109.79
Silage produced for biomethane (MtDM)	1.35	1.39	1.43
Slurry produced on biomethane farms (Mm^3)	0	0	0
Slurry imported from non-biomethane farms (Mm^3)	16.99	17.42	17.91
Energy produced from biomethane, excl. imports (TWh)	4.19	4.29	4.41
Energy produced from biomethane, incl. imports (TWh)	5.72	5.86	6.02
Scenario 2: Partial conversion		**Partial**	
Number of biomethane farms (% out of total farms)		38,083 (71.8%)	
Pasture dedicated to biomethane (kha)		79.21	
Silage produced for biomethane (MtDM)		1.03	
Slurry produced on biomethane farms (Mm^3)		12.92	
Slurry imported from non-biomethane farms (Mm^3)		0	
Energy produced from biomethane, excl. imports (TWh)		4.35	
Energy produced from biomethane, incl. imports (TWh)		4.35	

4.3 Overall financial costs and benefits

The combined impact on farmers varies greatly across scenarios (see Table 4.4). In the efficiency and profit scenarios, farmers experience combined income gains of around 15 and 47 million euros, respectively. In contrast, in the partial, and particularly in the climate scenario, they experience a net income loss (around 79 million and 113 million euros, respectively). This is as expected, as the farms in the profit scenario have a much lower average income than those in the climate and partial scenarios.

Additionally, while the financial cost to the farmers of reducing their herd size is accounted for in the income change, it is nevertheless important to point out the cattle lost, as this is also a loss in terms of available food. The reduction in herd size ranges from around 100,000 livestock units in the profit scenario to almost 300,000 livestock units in the climate scenario (see Table 4.4).

4.4 Distributional impacts

Looking at inequality as measured by the Gini coefficient, the efficiency, profit, and partial scenarios all show improvements over the status quo (see Tables 4.5 and 4.6). The impact on income across scenarios is more complicated. In the profit scenario, cattle farmers' income increases by 8.7%, leading to an overall

Table 4.4: Overall financial costs and benefits

Scenario 1: Total conversion	**Efficiency**	**Profit**	**Climate**
Net total income change (M€)	15.14	47.12	-112.95
Reduction in herd size (lu)	142,381	108,791	295,207
Scenario 2: Partial conversion		**Partial**	
Net total income change (M€)		-78.60	
Reduction in herd size (lu)		156,682	

decrease in inequality of 3.4% across all farms. In the efficiency scenario, cattle farmers' income increases by 5% while dairy farmers' income decreases by 0.9%, resulting in a 2.1% decrease in overall inequality. In the climate scenario, on the other hand, farmers experience a drop in income from switching to biomethane silage production, given that they have much higher original income levels. As a result, the average income of dairy farmers in the climate scenario drops by 7% and that of cattle farmers by 4.3%, indicating that switching to biomethane silage production is not an attractive option for high-emitting farms. A 2% increase in inequality accompanies this drop in income. Finally, the partial scenario sees average income losses of 0.4% for cattle farmers and 6% for dairy farmers. Overall inequality decreases by 1.6% under this scenario, indicating that the farms that lose out are those with initially higher incomes.

Table 4.5: Farm family income by farm type (in €)

	Cattle farms	**Dairy farms**	**All farms**
Original	14,129	84,291	34,202
Scenario 1: Total conversion			
Efficiency	14,838 (+5.0%)	83,521 (-0.9%)	34,488 (+0.8%)
Profit	15,359 (+8.7%)	84,327 (+0.0%)	35,090 (+2.6%)
Climate	13,526 (-4.3%)	78,353 (-7.0%)	32,072 (-6.2%)
Scenario 2: Partial conversion			
Partial	14,068 (-0.4%)	79,263 (-6.0%)	32,720 (-4.3%)

Table 4.6: Inequality (measured by the Gini coefficient) by scenario

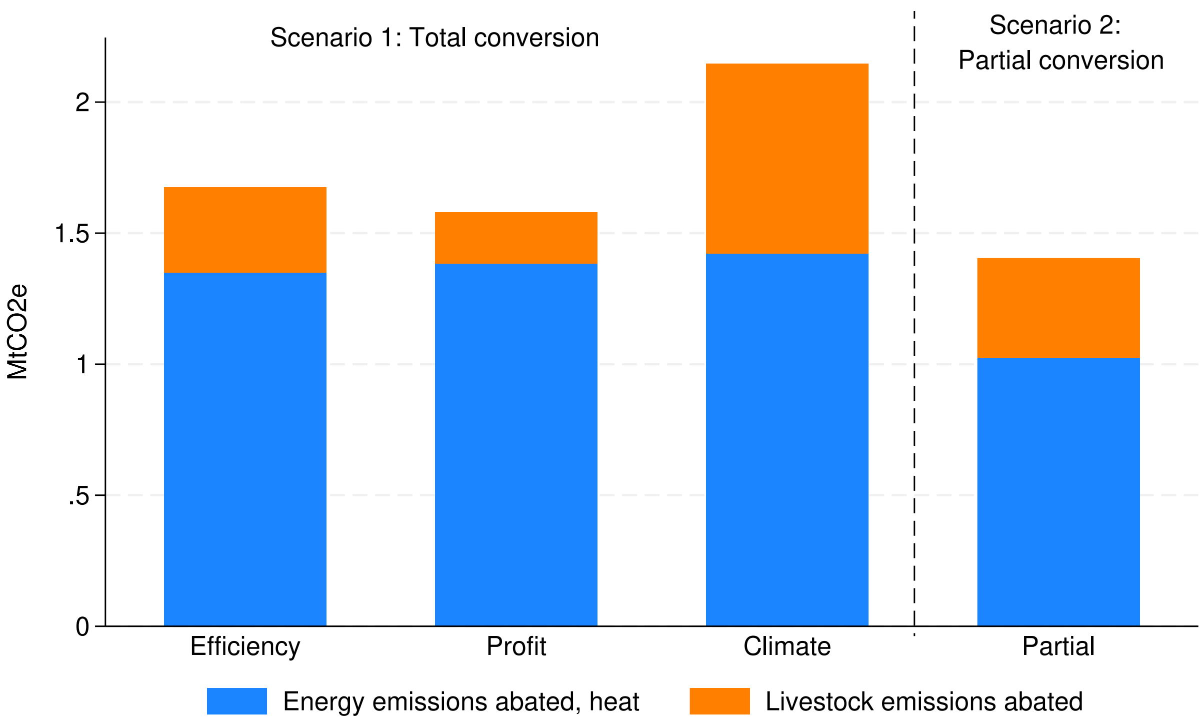
	Cattle farms	**Dairy farms**	**All farms**
Original	.547	.348	.615
Scenario 1: Total conversion			
Efficiency	.515 (-5.9%)	.356 (+2.3%)	.602 (-2.1%)
Profit	.509 (-6.9%)	.347 (-0.3%)	.594 (-3.4%)
Climate	.556 (+1.6%)	.382 (+9.8%)	.627 (+2.0%)
Scenario 2: Partial conversion			
Partial	.541 (-1.1%)	.344 (-1.1%)	.605 (-1.6%)

Our sensitivity analysis shows that both income and the Gini are moderately impacted by changes to the grass silage ratio (a change of between 0 and 2.3 percentage points difference to the main analysis), with no change in the direction of the overall findings. However, both income and the Gini are susceptible to changes in the silage price, with the direction of a scenario's overall impact flipping in several instances[3]. This result is partly driven by the large variation in expected silage prices and highlights the extent to which identified distributional outcomes depend on assumptions about silage prices.

4.5 Abatement potential

The abatement potential of each scenario is composed of (1) emissions abated from biomethane replacing fossil fuels, and (2) reduced enteric fermentation, i.e., methane emissions, as a result of reduced livestock numbers. All sub-scenarios in scenario 1 produce roughly the same amount of biomethane; therefore, all abate roughly the same amount of energy-related emissions, namely just under 1.4 $MtCO_2e$. However, they differ substantially in terms of livestock emissions abated, in line with the different reductions in herd size. While the profit scenario reaches 1.6 $MtCO_2e$ in total emissions abated, the efficiency scenario sees an abatement of 1.7 $MtCO_2e$, and the climate scenario of 2.1 $MtCO_2e$. The partial scenario abates 1.4 $MtCO_2e$, with around 1 $MtCO_2e$ from energy and around 0.4 $MtCO_2e$ from livestock. Overall, in terms of emissions abatement, the climate scenario clearly dominates the other scenarios (see Figure 2 for a graphical representation).

Figure 2: Emissions abatement from agricultural biomethane if RED conditions are met



Note: For scenario 1 the energy emissions abated assume that the grass silage is mixed in a 3:2 (silage:slurry) ratio with slurry from external farms and the emissions saved from the resulting energy allocated according to contribution to overall energy production. In practice, the largest emissions savings generally arise from the use of slurry, which, however, contributes less to the overall energy content.

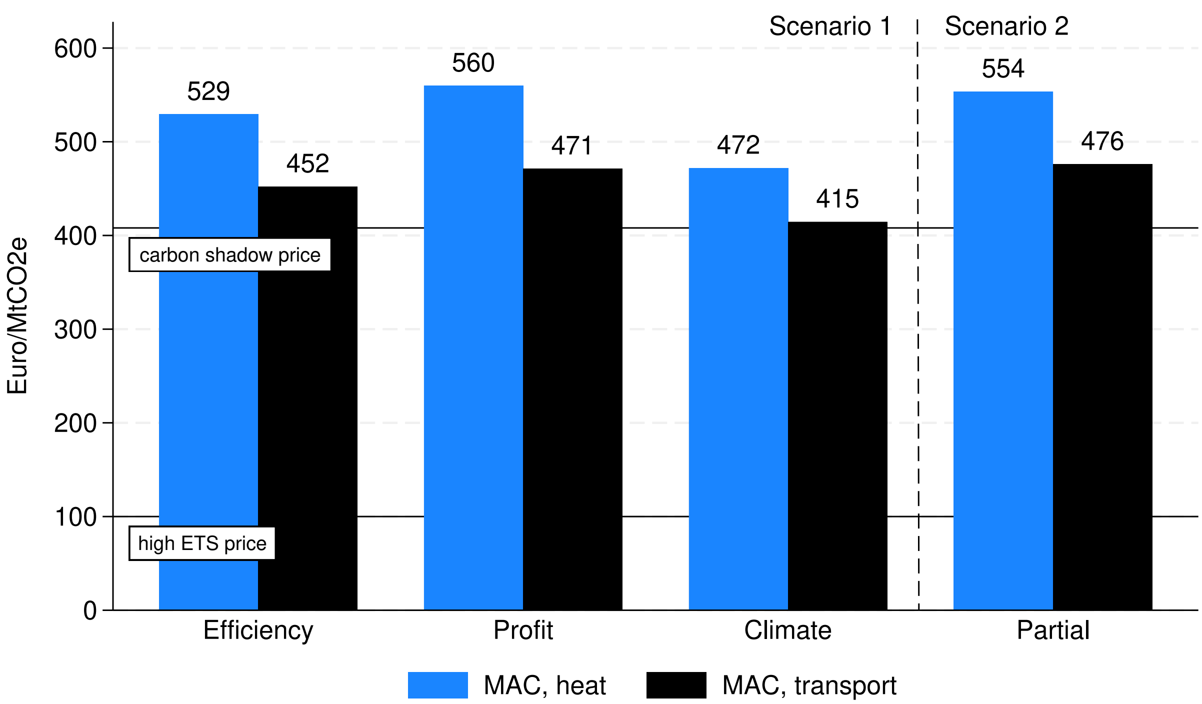
[3] The full results of the sensitivity analysis can be accessed in the supplementary materials.

Among the parameters varied in our sensitivity analysis, the abatement potential is affected only by the assumed emissions savings. The high and low emissions savings values consistently increase or decrease overall abatement potential by between 6 and 10% compared to the original analysis. In reality, the silage-to-slurry ratio also affects abatement potential, but we do not model this relationship endogenously and therefore cannot account for it in the sensitivity analysis.

4.6 Marginal abatement cost

All scenarios are above the shadow price of carbon estimate for 2030 (€408/$MtCO_2e$) (see Figure 3). The MACs for the efficiency, profit, and partial scenarios are all within €30 of each other, between €500 and €600 when replacing fossil gas for heat, or around €100 lower when used for transport. The end use clearly makes a substantial difference to the marginal abatement cost, given the emissions intensity of the fossil fuels being replaced by biomethane. The climate scenario has the lowest marginal abatement cost by a large margin. This has a MAC of €472/tCO_2e for heat and €415/tCO_2e for transport, with the latter close to the shadow price of carbon estimated for 2030. This price is explained by the significant contribution of livestock emissions abatement in this scenario. As shown in the previous section, this means that overall emissions abatement is much higher than in the other scenarios, for the same amount of biomethane.

Figure 3: Marginal abatement cost (MAC) of agricultural biomethane by scenario and end use



Note: The upper horizontal line represents the shadow price of carbon for 2030 as calculated by Kevany and Foley (2024). The lower horizontal line represents a high price under the European Union Emissions Trading Scheme (ETS) over the period from its inception to early 2026 (see, e.g., Trading Economics, 2025, accessed 16/02/2026).

Our sensitivity analysis shows that the marginal abatement cost is affected not only by the assumptions regarding emissions savings but also, more substantially, by the biomethane price, as the latter affects biomethane revenues. Changes to the emissions savings increase (for low emissions savings) and decrease (for high emissions savings) the MAC by between 6 and 9% across the different scenarios. A low gas/biomethane price, about €20/MWh below the original, leads to an increase in the MAC of about 8-9%. However, a high estimate of the biomethane price is about €60/MWh higher than the base price and, as a result, the MAC could decrease by between 20 and 24% compared to the original analysis. This would bring it below the original shadow price of carbon for all scenarios if used in transport, although only for the climate scenario if used for heat.

5 Discussion and conclusion

Supporting a Just transition is a central aim of the European Union to ensure that the shift towards a climate-neutral economy is fair and inclusive. For farmers to implement sustainable practices, those practices must be economically feasible. To the best of our knowledge, this article is the first comprehensive analysis of the social costs and benefits of biomethane production focusing on distributional impacts. We propose a microsimulation model for the farming sector that tracks changes in the farm income distribution and quantifies the immediate climate benefits of biomethane production.

While the European roadmap for the scaling up of biomethane acknowledges the potential income gains for farmers, no specific policy instruments are considered (European Commission, 2022). Focusing on specialised dairy and beef farms, our research identifies which farmers could be targeted to achieve different policy goals, namely farm efficiency, farm profitability, and emission reductions, as well as an intermediate non-targeted scenario which sees most farms switching a small portion of their operations. The four scenarios provide insight into the expected distributional impacts and emissions reductions, depending on the composition of farmers contributing to the 5.7 TWh target set by the Irish government. In practice, the number of farmers contributing to this target will depend on farmer preferences, policy priorities, and regulations.

Our scenarios indicate that the profiles of farms that would need to contribute to biomethane production vary widely depending on these preferences and priorities. No scenario emerged as dominant among the four scenarios; each had its advantages and disadvantages. The most likely to be aligned with farmer preferences is the 'profit scenario'. Our findings for this scenario demonstrate that there are enough low-income farms for which it would be economically beneficial to switch to grass silage for biomethane production. This would lead to decreased inequality and increased farm incomes. These results align with Geoghegan and O'Donoghue (2024), who find that 4% of total agricultural land, or 187,377 ha, is more profitable under biomethane silage than current land use, which is higher than what is required to reach the 5.7 TWh target if farms fully dedicate their pasture to this purpose. While Geoghegan and O'Donoghue (2024) do not limit their analysis to specialized cattle and dairy farms, 89% of the land they identify is currently under cattle. In our model, we go one step further and outline more detailed characteristics of the farms that would switch under this scenario. The profile of these farms indicates that, under this scenario, the most environmentally sustainable and extensive farms would be those transitioning away from livestock farming, leading to a consolidation of livestock farming into high-intensity farms. This concern is shared by Magnolo et al. (2024), who cite several examples of biogas/biomethane production leading to intensified land use and crowding out smaller farms. However, in their examples, the process is driven by concentrated animal feeding operations rather than by pasture-based systems such as those on Ireland's cattle and dairy farms. Looking at farmer motivation and ability to switch, the very low income levels of the farms in the profit scenario suggest that the selected farmers may be driven by motives other than profit to maintain their current farming operations, or lack the resources to change them. This would need to be investigated further to assess the practical feasibility of this scenario.

If high-emitting farms switched instead, this would yield greater emissions benefits but would entail higher opportunity costs for farmers, given much higher original income levels. This option also substantially increased inequality within the farming population. Nevertheless, even accounting for income losses, the marginal abatement cost was the lowest, although still very high, for this scenario. Thus, it is unlikely that high-emitting farmers will switch on their own, and so incentives or other policies may be required to enable such a transition. Given the high stocking rates on farms in this scenario, it might be possible to align nitrogen-reduction targets with biomethane targets under this pathway. High stocking rates are known to lead to nitrogen pollution (Giustini et al., 2007), and Ireland has experienced a severe deterioration in water quality as a result of agricultural activity (Environmental Protection Agency, 2021). If farms with high stocking rates converted a small portion of their pasture to low-input multi-species swards for biomethane production and reduced their herd size accordingly, as described for the 'partial scenario', this would minimise ammonia emissions both through the land use change and by ensuring that the slurry that is collected would not be landspread on the producing farm. As demonstrated by the 'partial scenario', such a partial conversion of farmland would not be sufficient to meet biomethane targets, but could be a contributing factor. Dairy farmers are more interested in adopting on-farm anaerobic digestion than beef farmers (O'Connor et al., 2021), so involving them in the energy production process could be a pathway to creating the incentive structure for at least a partial switch in land use. However, such an approach would have to be guided carefully, as there is potential for it to have the opposite effect and farmers involved in energy production to be incentivised to intensify their farming operations (Magnolo et al., 2024, pp. 4-5).

The marginal abatement cost we calculate in our model is on the high end of marginal abatement costs found for biomethane in Ireland, which ranges from a negative abatement cost of -€200/tCO_2e to €500/tCO_2e (Teagasc Greenhouse Gas Working Group, 2019; Environmental Protection Agency Ireland (EPA), 2019; Climate Change Advisory Council Ireland, 2020; Bose et al., 2022b; Wu et al., 2023; Teagasc, 2023). This can largely be attributed to the feedstocks and the chosen feedstock ratio. Where other authors investigate the MAC specifically for grass silage and slurry, they generally do so on approximately a 4:1 silage:slurry VS ratio or 50% slurry on a fresh weight basis (Environmental Protection Agency Ireland (EPA), 2019; SEAI, 2022; Bose et al., 2022b; Wu et al., 2023) which is more economically profitable than the 3:2 VS ratio applied here. However, it is questionable if a 4:1 ratio would achieve sufficient emissions reductions to qualify as renewable energy under the Renewable Energy Directive (Beausang et al., 2021). In fact, the environmentally optimal ratio, as found by Beausang et al. (2021), is a 2:3 silage to slurry ratio in VS terms[4].

However, our sensitivity analysis indicates that, at higher biomethane prices, the marginal abatement cost across all scenarios could fall to between 300 and 400 €/$MtCO_2e$,below the Irish government's shadow price of carbon, if used in transport. Although only if the highest emitting farms switched would this be the case

[4]While higher slurry ratios reduce freshwater eutrophication and global warming potential, they lead to terrestrial acidification (Beausang et al., 2021).

for use as heat. A higher price for biomethane compared to fossil gas could be achieved through renewable gas certificates, with certification already provided by the Irish gas networks provider.

Ultimately, agricultural biomethane feedstock cultivation has the potential to contribute to a Just energy transition by reducing inequality among farmers while meeting renewable energy targets, though at a high marginal abatement cost. However, there is likely tension between reducing inequality, maximising emissions reductions, and minimising costs, as well as the need to consider which long-term structural changes in the farming landscape are desirable.

Our analysis does have some limitations. The latest farm data available to us was from 2017, and since then, the farming landscape in Ireland has continued to evolve, which this analysis could not capture. Additionally, the lack of spatial data prevented us from assessing whether the slurry required for import in scenario 1 would be available from nearby farms. A first spatial analysis by Geoghegan and O'Donoghue (2024) indicates that farms for which it would be economically beneficial to switch to grass silage production are distributed fairly evenly throughout Ireland at an electoral district level. However, they do not directly assess the availability of the required slurry volume near these potential biomethane farms. Further research should integrate spatial datasets with farm-level characteristics to build on our analysis and assess the practical feasibility of slurry provision and farmer motivation to provide biomethane feedstocks. Finally, an element we did not consider here but that deserves further attention is the possibility of poor harvests, as was the case in Ireland during the summer 2018 drought (Zhu et al., 2019). Since droughts are likely to worsen due to climate change (Meresa and Murphy, 2023), this should be given greater consideration.

Acknowledgements

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Appendix

Appendix I: Summary Statistics - Panel Data

Table 5.1: Summary statistics - National Farm Survey data, 2000 - 2017

	Cattle farms	Dairy farms	Total
N	6,845 (51.1%)	6,561 (48.9%)	13,406 (100.0%)
Average land farmed (ha)	42 (26)	58 (31)	50 (30)
Civil status of main farmer			
Single	2,213 (32.3%)	1,303 (19.9%)	3,516 (26.2%)
Married	4,632 (67.7%)	5,258 (80.1%)	9,890 (73.8%)
Gender of main farmer			
Man	6,470 (94.5%)	6,420 (97.9%)	12,890 (96.2%)
Woman	375 (5.5%)	141 (2.1%)	516 (3.8%)
Age of main farmer	55 (12)	50 (11)	53 (12)
Average farm family income (€)	14,433 (16,024)	49,765 (38,661)	31,725 (34,271)
Average livestock units	49 (38)	105 (61)	76 (58)
Pasture area %	89 (18)	92 (14)	90 (16)
Stocking rate (lu/ha)	1.4 (.57)	2 (.55)	1.7 (.64)
High environmental subsidies			
No	4,130 (60.3%)	5,026 (76.6%)	9,156 (68.3%)
Yes	2,715 (39.7%)	1,535 (23.4%)	4,250 (31.7%)

Note: For continuous variables, the mean is displayed with the standard deviation shown in brackets. For factor variables, the frequency is shown with the percentage in brackets.

Appendix II: Stochastic Frontier Analaysis - Estimation

To estimate our model, we assume the following translog functional form for the production function:

$$\begin{aligned}\ln Y_{it} = \beta_0 + \sum_{k=1}^{K} \beta_k \ln X_{itk} + \frac{1}{2} \sum_{k=1}^{K} \sum_{g=1}^{K} \beta_{gk} \ln X_{itk} \ln X_{itg} + \\ + \beta_t t + \frac{1}{2} \beta_{tt} t^2 + \sum_{k=1}^{K} \beta_{tk} \ln X_{itk} t + v_{it} - u_{it}\end{aligned} \tag{7}$$

We include an interaction between the time trend t and the vector of inputs $\mathbf{X_{itk}}$ to account for non-neutral technological change. The Cobb-Douglas function is nested in this functional form; therefore, we test the preferred specification with a likelihood ratio test. The parameters we want to estimate are $\beta_0, \beta_k, \beta_{gk}, \beta_t, \beta_{tt}$, and β_{tk}.

A potential problem is that if farm-specific unobserved heterogeneity does not vary over time, the common intercept β_0 in equation (7) can introduce a bias. To avoid this problem, we estimate our model by applying panel estimation techniques, namely True Fixed Effects (TFE) and True Random Effects (TRE). The TFE estimation approach replaces the uniform intercept β_0 with multiple farm-specific intercepts (β_i), while the TRE approach introduces a random constant (β) and farm-specific random terms (α_i) instead (Greene, 2005).

Finally, two assumptions about the distribution of the two error terms in equations (1) and (7) are necessary to estimate our model:

$$\begin{aligned}u_{it} \sim N^{+}(0, \sigma^2_{itu}), \text{ with } \sigma^2_{itu} = \exp(\gamma_m Z_{itm}) \\ v_{it} \sim N(0, \sigma^2_{itv})\end{aligned} \tag{8}$$

Here, m is an index for the number of inefficiency drivers included in the model. Following Caudill et al. (1995), we specify the inefficiency term u_{it} as having a constant mean of 0 and a variance of σ^2_{itu}. The variance depends on a set of estimated parameters (γ) and a vector of inefficiency drivers ($\mathbf{Z_{it}}$).

Appendix III: Stochastic Frontier Analysis - Results

Table 5.2: Stochastic frontier analysis of all cattle and dairy farms

	(1) Cattle farms	(2) Dairy farms	(3) All farms
Technical efficiency	0.61	0.82	0.71
Inefficiency analysis			
Good soil (soil group 1)	-0.273***	-0.341***	-0.266***
	(0.055)	(0.058)	(0.037)
Share pasture	0.237*	-0.348	-0.0185
	(0.118)	(0.187)	(0.092)
Share unpaid labour units	2.357***	1.790***	3.415***
	(0.276)	(0.178)	(0.142)
Off-farm work	0.0733	0.403***	0.577***
	(0.055)	(0.112)	(0.044)
Good soil x off-farm work	0.164	0.354*	0.203**
	(0.084)	(0.149)	(0.066)
Married	0.00593	-0.463***	-0.265***
	(0.045)	(0.062)	(0.035)
Woman	0.243**	0.668***	0.561***
	(0.090)	(0.160)	(0.077)
Constant	-2.936***	-3.373***	-4.088***
	(0.294)	(0.247)	(0.165)
Observations	6844	6560	13413

Standard errors in parentheses; N for all farms technical efficiency = 13,404

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Appendix IV: CAPEX equations

CAPEX anaerobic digestion:

$$\text{CAPEX}_{AD} = \text{Number of AD Plants} \times 554.89 \times \left(\frac{\text{Total Feedstock FM}}{\text{Number of AD Plants}}\right)^{0.841} \times \left(\frac{\text{CEPCI}_{2023}}{\text{CEPCI}_{2008}}\right) \quad (9)$$

Where *total feedstock FM/number AD plants* represents the tons of fresh matter per AD plant and *CEPCI* is the chemical engineering plant cost index for the respective years (Maxwell, 2024).

CAPEX upgrading plants:

$$\text{Biogas Flow} = \frac{(\text{Total Silage VS} + \text{Total Slurry VS}) \times \text{SMY}_{32}}{\text{Number of AD Plants}} \quad (10)$$

$$\text{CAPEX}_{Up} = \text{Number of AD Plants} \times 181,613 \times \left(\frac{\text{Biogas Flow}}{\text{Operating Hours} \times \%\text{CH}_4}\right)^{0.373} \times \left(\frac{\text{CEPCI}_{2023}}{\text{CEPCI}_{2013}}\right) \quad (11)$$

Where *total silage VS* and *total slurry VS* are the total volatile solids from each of the feedstock sources across all biomethane farms and imported slurry; *SMY32* is the average specific methane yield for a 3:2 silage to slurry ratio (i.e., 324 m3CH4/tVS; Wall et al., 2014, Table 3); *operating hours* are the hours the upgrading plant operates a year (i.e., 8585 h/a; Padi et al., 2023); and *%CH4* is the average methane content of biogas for a 3:2 silage to slurry ratio (i.e., 54%; Wall et al., 2014, Table 2).

Appendix V: Values used in the sensitivity analysis

Table 5.3: Sensitivity analysis values

Parameters	Values	Units	References
Feedstock variables			
Silage price	14	€/tFM	Padi et al. 2023, price required for small biomethane plants to be profitable
	47	€/tFM	SEAI 2022, pp. 51-55
	56	€/tFM	Padi et al. 2023, maximum viable price for medium to large biomethane plants to be profitable
Silage to slurry ratio (on VS basis)	2:3	ratio	Beausang et al. 2021, most environmentally sustainable option
	3:2	ratio	Beausang et al. 2021
	4:1	ratio	Most commonly used in the Irish biomethane literature; economically preferable to lower ratios (O'Shea et al., 2017)
Biomethane production variables			
Biomethane price	25	€/MWh	Trading Economics, lowest fossil gas price value between March 2024 and March 2025; no added carbon tax
	47.52	€/MWh	Fossil gas price from Trading Economics, accessed on September 5th, 2024, combined with Natural Gas Carbon Tax from Revenue 2025
	105	€/MWh	Sustainable Energy Authority of Ireland (SEAI) 2022
Emissions variables			
Energy emissions savings, heat	0.2138	tCO_2e/MWh	Ó Céileachair et al. 2022, assuming 1% methane leakage
	0.2361	tCO_2e/MWh	Assuming REDII conditions for heat are met as in Long and Murphy 2019, Table 5
	0.2610	tCO_2e/MWh	Ó Céileachair et al. 2022, assuming 3.55% methane leakage
Carbon shadow price	73.01	€/tCO_2e	ETS price according to Trading Economics 2025, accessed 21/03/2025
	408	€/tCO_2e	Kevany and Foley 2024, for the year 2030

Note: These are the values used in the sensitivity analysis. For each parameter, the first value is the low value, the second is the one used in the original analysis, and the third is the high value. The exception is the shadow price where no high value was included.

References

Dennis Aigner, CA Knox Lovell, and Peter Schmidt. Formulation and estimation of stochastic frontier production function models. *Journal of Econometrics*, 6(1):21–37, 1977.

Eoin Allen, David M. Wall, Christiane Herrmann, and Jerry D. Murphy. A detailed assessment of resource of biomethane from first, second and third generation substrates. *Renewable Energy*, 87:656–665, March 2016. ISSN 0960-1481. doi: 10.1016/j.renene.2015.10.060. URL https://www.sciencedirect.com/science/article/pii/S0960148115304134.

Filomena Ardolino, Francesco Parrillo, and Umberto Arena. Biowaste-to-biomethane or biowaste-to-energy? An LCA study on anaerobic digestion of organic waste. *Journal of Cleaner Production*, 174:462–476, February 2018. ISSN 0959-6526. doi: 10.1016/j.jclepro.2017.10.320. URL https://www.sciencedirect.com/science/article/pii/S0959652617326240.

Ciara Beausang, Kevin McDonnell, and Fionnuala Murphy. Assessing the environmental sustainability of grass silage and cattle slurry for biogas production. *Journal of Cleaner Production*, 298:126838, May 2021. ISSN 0959-6526. doi: 10.1016/j.jclepro.2021.126838. URL https://www.sciencedirect.com/science/article/pii/S095965262101057X.

A. Bose, R. O'Shea, R. Lin, A. Long, K. Rajendran, D. Wall, S. De, and J. D. Murphy. Evaluation of a biomethane, food and biofertiliser polygeneration system in a circular economy system. *Renewable and Sustainable Energy Reviews*, 170:112960, December 2022a. ISSN 1364-0321. doi: 10.1016/j.rser.2022.112960. URL https://www.sciencedirect.com/science/article/pii/S1364032122008413.

Archishman Bose, Richard O'Shea, Richen Lin, Aoife Long, Karthik Rajendran, David Wall, Sudipta De, and Jerry D. Murphy. The marginal abatement cost of co-producing biomethane, food and biofertiliser in a circular economy system. *Renewable and Sustainable Energy Reviews*, 169:112946, November 2022b. ISSN 1364-0321. doi: 10.1016/j.rser.2022.112946. URL https://www.sciencedirect.com/science/article/pii/S1364032122008279.

Steven B Caudill, Jon M Ford, and Daniel M Gropper. Frontier Estimation and Firm-Specific Inefficiency Measures in the Presence of Heteroscedasticity. *Journal of Business & Economic Statistics*, 13(1):105–111, 1995.

Enrique Chan Gutiérrez, David M. Wall, Richard O'Shea, Roger Méndez Novelo, Miguel Moreno Gómez, and Jerry D. Murphy. An economic and carbon analysis of biomethane production from food waste to be used as a transport fuel in Mexico. *Journal of Cleaner Production*, 196:852–862, September 2018. ISSN 0959-6526. doi: 10.1016/j.jclepro.2018.06.051. URL https://www.sciencedirect.com/science/article/pii/S0959652618317013.

Gaetano Chinnici, Roberta Selvaggi, Mario D'Amico, and Biagio Pecorino. Assessment of the potential energy supply and biomethane from the anaerobic digestion of agro-food feedstocks in Sicily. *Renewable and Sustainable Energy Reviews*, 82:6–13, February 2018. ISSN 1364-0321. doi: 10.1016/j.rser.2017.09.018. URL https://www.sciencedirect.com/science/article/pii/S1364032117312510.

Jeerasak Chobtang, Stewart F. Ledgard, Sarah J. McLaren, and Daniel J. Donaghy. Life cycle environmental impacts of high and low intensification pasture-based milk production systems: A case study of the Waikato region, New Zealand. *Journal of Cleaner Production*, 140:664–674, January 2017. ISSN 0959-6526. doi: 10.1016/j.jclepro.2016.06.079. URL https://www.sciencedirect.com/science/article/pii/S0959652616307569.

Climate Change Advisory Council Ireland. Annual Review 2020. Technical report, September 2020.

Climate Change Advisory Council Ireland. Carbon Budgets to Inform Climate Action: A society-wide, integrated GHG quota and accounting perspective. (Working Paper No. 19), July 2023.

CSO. Land Use Environmental Indicators Ireland 2022, November 2022. URL https://www.cso.ie/en/releasesandpublications/ep/p-eii/environmentalindicatorsireland2022/landuse/. Publisher: CSO.

CSO. Farm Structure Farm Structure Survey 2023 - Central Statistics Office, December 2024. URL https://www.cso.ie/en/releasesandpublications/ep/p-fss/farmstructuresurvey2023/farmstructure/.

Federica Cucchiella and Idiano D'Adamo. Technical and economic analysis of biomethane: A focus on the role of subsidies. *Energy Conversion and Management*, 119:338–351, July 2016. ISSN 0196-8904. doi: 10.1016/j.enconman.2016.04.058. URL https://www.sciencedirect.com/science/article/pii/S0196890416303089.

Magdalena M Czyrnek-Delêtre, Eoin P Ahern, and Jerry D Murphy. Is small-scale upgrading of landfill gas to biomethane for use as a cellulosic transport biofuel economically viable? *Biofuels, Bioproducts and Biorefining*, 10(2):139–149, 2016. ISSN 1932-1031. doi: 10.1002/bbb.1627. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/bbb.1627. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/bbb.1627.

DAFM and DECC. Ireland's National Biomethane Strategy. Technical report, Government of Ireland, May 2024.

Bronwyn Dowd, Declan McDonnell, and Maria G. Tuohy. Current Progress in Optimising Sustainable Energy Recovery From Cattle Paunch Contents, a Slaughterhouse Waste Product. *FRONTIERS IN SUSTAINABLE FOOD SYSTEMS*, 6, May 2022. doi: 10.3389/fsufs.2022.722424. Place: AVENUE DU TRIBUNAL FEDERAL 34, LAUSANNE, CH-1015, SWITZERLAND Publisher: FRONTIERS MEDIA SA Type: Review.

P Duffy, K Black, B Hyde, A M Ryan, and J Ponzi. Ireland's National Inventory Report 2019 - Greenhouse Gas Emissions 1990 - 2017. Technical report, Environmental Protection Agency Ireland, 2019.

Environmental Protection Agency. Urgent action needed to curb nitrogen pollution in Ireland's waters, says EPA, July 2021. URL https://www.epa.ie/news-releases/news-releases-2021/urgent-action-needed-to-curb-nitrogen-pollution-in-irelands-waters-says-epa.php.

Environmental Protection Agency. Greenhouse gas emissions: Agriculture, n. d. URL https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/agriculture/.

Environmental Protection Agency Ireland (EPA). The Role of Incentivising Biomethane in Ireland Using Anaerobic Digestion. EPA Research Report 279, Environmental Protection Agency Ireland, 2019. URL https://www.epa.ie/publications/research/waste/Research_Report_279.pdf.

Environmental Protection Agency Ireland (EPA), Jerry D. Murphy, Nicholas E. Korres, Anoop Singh, Beatrice Smyth, Abdul-Sattar Nizami, and Thanasit Thamsiriroj. The Potential for Grass Biomethane as a Biofuel. CCRP Report, Environmental Protection

Agency Ireland, 2011. URL https://www.epa.ie/publications/research/climate-change/CCRP11---The-Potential-for-Grass-Biomethane-as-a-Biofuel.pdf.

European Commission. REPowerEU Plan, May 2022. URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483.

European Parliament and Council of the European Union. Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (recast), December 2018. URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG.

FAO. Fodder management: Hay and silage making, 2002. URL https://openknowledge.fao.org/server/api/core/bitstreams/67aac8f6-0799-4c8e-89a7-1da6126f125f/content. Accessed 22 July 2026.

Cathal Geoghegan and Cathal O'Donoghue. An analysis of the social and private return to land use change from agriculture to renewable energy production in Ireland. *Journal of Cleaner Production*, 385:135698, January 2023. ISSN 09596526. doi: 10.1016/j.jclepro.2022.135698. URL https://linkinghub.elsevier.com/retrieve/pii/S0959652622052726.

Cathal Geoghegan and Cathal O'Donoghue. A spatial analysis of the economic returns to land-use change from agriculture to renewable energy production: Evidence from Ireland. *GCB Bioenergy*, 16(9):e13185, 2024. ISSN 1757-1707. doi: 10.1111/gcbb.13185. URL https://onlinelibrary.wiley.com/doi/abs/10.1111/gcbb.13185. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/gcbb.13185.

Lorenzo Giustini, Anna Acciaioli, and Giovanni Argenti. Apparent balance of nitrogen and phosphorus in dairy farms in Mugello (Italy). *Italian Journal of Animal Science*, 6(2):175–185, January 2007. ISSN null. doi: 10.4081/ijas.2007.175. URL https://doi.org/10.4081/ijas.2007.175. Publisher: Taylor & Francis _eprint: https://doi.org/10.4081/ijas.2007.175.

Government of Ireland. Climate Action and Low Carbon Development Act 2015 - REVISED - Updated to 12 October 2021, December 2015. URL https://revisedacts.lawreform.ie/eli/2015/act/46/revised/en/html#SEC6.

Government of Ireland. European Union (Good Agricultural Practice for Protection of Waters) Regulations 2022 S.I. No. 113 of 2022, 2022a. URL https://www.irishstatutebook.ie/eli/2022/si/113/made/en/pdf.

Government of Ireland. Sectoral Emissions Ceilings: September 2022, September 2022b. URL https://www.gov.ie/pdf/?file=https://assets.gov.ie/234926/2ebb2431-d558-4a54-a15c-605817c37b2f.pdf#page=null.

Government of Ireland. Climate Action Plan 2023: Changing Ireland for the Better. Technical report, 2023. URL https://www.gov.ie/en/publication/6223e-climate-action-plan-2021/.

Government of Ireland. Ireland's National Biomethane Strategy, May 2024. URL https://www.gov.ie/pdf/?file=https://assets.gov.ie/294685/3de4b66e-ff15-410e-9211-260e08d93b14.pdf#page=null.

Willam Greene. Fixed and random effects in stochastic frontier models. *Journal of Productivity Analysis*, 23(1):7–32, 2005.

Rohit Gupta, Royce Miller, William Sloan, and Siming You. Economic and environmental assessment of organic waste to biomethane conversion. *Bioresource Technology*, 345:126500, February 2022. ISSN 0960-8524. doi: 10.1016/j.biortech.2021.126500. URL https://www.sciencedirect.com/science/article/pii/S0960852421018423.

Ke He, Junbiao Zhang, and Yangmei Zeng. Rural households' willingness to accept compensation for energy utilization of crop straw in China. *Energy*, 165:562–571, December 2018. ISSN 0360-5442. doi: 10.1016/j.energy.2018.09.023. URL https://www.sciencedirect.com/science/article/pii/S0360544218317833.

IEA. Outlook for biogas and biomethane: Prospects for organic growth. World Energy Outlook Special Report, 2020. URL https://iea.blob.core.windows.net/assets/03aeb10c-c38c-4d10-bcec-de92e9ab815f/Outlook_for_biogas_and_biomethane.pdf.

IEA Bioenergy. The role of Anaerobic Digestion and Biogas in the Circular Economy. Technical report, August 2018.

Intergovernmental Panel On Climate Change. *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 1 edition, July 2021. ISBN 978-1-00-915789-6. doi: 10.1017/9781009157896. URL https://www.cambridge.org/core/product/identifier/9781009157896/type/book.

ISSDA. Irish Social Science Data Archive: Teagasc National Farm Survey, 2000 - 2017. URL https://www.ucd.ie/issda/data/teagascnationalfarmsurvey/. Publisher: Irish Social Science Data Archive.

Laura Kevany and Niamh Foley. Revising the Shadow Price of Carbon used in Public Sector Economic Appraisal. Technical report, Government of Ireland, March 2024.

Subal C Kumbhakar, Gudbrand Lien, and J Brian Hardaker. Technical efficiency in competing panel data models: a study of Norwegian grain farming. *Journal of Productivity Analysis*, 41(2):321–337, 2014.

Lidia Lombardi and Giovanni Francini. Techno-economic and environmental assessment of the main biogas upgrading technologies. *Renewable Energy*, 156:440–458, August 2020. ISSN 0960-1481. doi: 10.1016/j.renene.2020.04.083. URL https://www.sciencedirect.com/science/article/pii/S0960148120306157.

Aoife Long and Jerry D. Murphy. Can green gas certificates allow for the accurate quantification of the energy supply and sustainability of biomethane from a range of sources for renewable heat and or transport? *Renewable and Sustainable Energy Reviews*, 115:109347, November 2019. ISSN 1364-0321. doi: 10.1016/j.rser.2019.109347. URL https://www.sciencedirect.com/science/article/pii/S1364032119305556.

Francesca Magnolo, Jeroen Candel, and Stijn Speelman. Biomethane from manure in the RePowerEU: A critical perspective on the scale-up of renewable energy production from the livestock sector. *Energy Research & Social Science*, 118:103793, December 2024. ISSN 2214-6296. doi: 10.1016/j.erss.2024.103793. URL https://www.sciencedirect.com/science/article/pii/S2214629624003840.

Pietro Marconi and Lorenzo Rosa. Role of biomethane to offset natural gas. *Renewable and Sustainable Energy Reviews*, 187:113697, November 2023. ISSN 1364-0321. doi: 10.1016/j.rser.2023.113697. URL https://www.sciencedirect.com/science/article/pii/S1364032123005543.

A. Mattioli, D. Boscaro, F. Dalla Venezia, F. Correale Santacroce, A. Pezzuolo, L. Sartori, and D. Bolzonella. Biogas from Residual Grass: A Territorial Approach for Sustainable Bioenergy Production. *Waste and Biomass Valorization*, 8(8):2747–2756, December 2017. ISSN 1877-265X. doi: 10.1007/s12649-017-0006-y. URL https://link.springer.com/article/10.1007/s12649-017-0006-y. Company: Springer Distributor: Springer Institution: Springer Label: Springer Number: 8 Publisher: Springer Netherlands.

Charles Maxwell. Cost Indices, October 2024. URL https://toweringskills.com/financial-analysis/cost-indices/.

Wim Meeusen and Julien van Den Broeck. Efficiency Estimation from Cobb-Douglas Production Functions with Composed Error. *International Economic Review*, pages 435–444, 1977.

Hadush Meresa and Conor Murphy. Climate change impacts on spatial and seasonal meteorological drought characteristics for the island of Ireland. *International Journal of Climatology*, 43(14):6523–6539, 2023. ISSN 1097-0088. doi: 10.1002/joc.8217. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/joc.8217. _eprint: https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1002/joc.8217.

T. Moloney, H. Sheridan, J. Grant, E.G. O'Riordan, and P. O'Kiely. Yield of binary- and multi-species swards relative to single-species swards in intensive silage systems. *Irish Journal of Agricultural and Food Research*, 59(1), 2021. ISSN 2009-9029. doi: 10.2478/ijafr-2020-0002. URL https://scienceopen.com/hosted-document?doi=10.2478/ijafr-2020-0002.

Jerry D. Murphy, James Browne, Eoin Allen, and Cathal Gallagher. The resource of biomethane, produced via biological, thermal and electrical routes, as a transport biofuel. *Renewable Energy*, 55:474–479, July 2013. ISSN 0960-1481. doi: 10.1016/j.renene.2013.01.012. URL https://www.sciencedirect.com/science/article/pii/S0960148113000372.

Richard O'Shea, David M. Wall, Ian Kilgallon, James D. Browne, and Jerry D. Murphy. Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region. *Applied Energy*, 188:237–256, February 2017. ISSN 0306-2619. doi: 10.1016/j.apenergy.2016.11.121. URL https://www.sciencedirect.com/science/article/pii/S0306261916317524.

Sean O'Connor, Ehiaze Ehimen, Suresh C. Pillai, Niamh Power, Gary A. Lyons, and John Bartlett. An Investigation of the Potential Adoption of Anaerobic Digestion for Energy Production in Irish Farms. *Environments*, 8(2):8, February 2021. ISSN 2076-3298. doi: 10.3390/environments8020008. URL https://www.mdpi.com/2076-3298/8/2/8. Number: 2 Publisher: Multidisciplinary Digital Publishing Institute.

Richard O'Shea, Ian Kilgallon, David Wall, and Jerry D. Murphy. Quantification and location of a renewable gas industry based on digestion of wastes in Ireland. *Applied Energy*, 175:229–239, August 2016. ISSN 0306-2619. doi: 10.1016/j.apenergy.2016.05.011. URL https://www.sciencedirect.com/science/article/pii/S0306261916305931.

Richard Kingsley Padi, Sean Douglas, and Fionnuala Murphy. Techno-economic potentials of integrating decentralised biomethane production systems into existing natural gas grids. *Energy*, 283:128542, November 2023. ISSN 0360-5442. doi: 10.1016/j.energy.2023.128542. URL https://www.sciencedirect.com/science/article/pii/S0360544223019369.

Valerio Paolini, Francesco Petracchini, Marco Segreto, Laura Tomassetti, Nour Naja, and Angelo Cecinato. Environmental impact of biogas: A short review of current knowledge. *Journal of Environmental Science and Health, Part A*, 53(10):899–906, August 2018. ISSN 1093-4529. doi: 10.1080/10934529.2018.1459076. URL https://doi.org/10.1080/10934529.2018.1459076. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/10934529.2018.1459076.

Revenue. Natural Gas Carbon Tax (NGCT), December 2025. URL https://www.revenue.ie/en/companies-and-charities/excise-and-licences/energy-taxes/natural-gas-carbon-tax/rate-of-tax.aspx.

SEAI. National Heat Study: Sustainable Bioenergy for Heat: Spatial Assessment of Resources and Evaluation of Costs and Greenhouse Gas Impacts. Technical Report 7, February 2022. URL https://www.seai.ie/publications/Sustainable-Bioenergy-for-Heat.pdf.

Sustainable Energy Authority of Ireland (SEAI). Bioenergy Supply in Ireland 2015 - 2035. Technical report, 2017a. URL https://www.seai.ie/publications/Bioenergy-Supply-in-Ireland-2015-2035.pdf.

Sustainable Energy Authority of Ireland (SEAI). Sustainability Criteria Options and Impacts for Irish Bioenergy Resources. Technical report, 2017b. URL https://www.seai.ie/publications/Sustainability-Criteria-Options-and-Impacts-for-Irish-Bioenergy-Resources.pdf.

Sustainable Energy Authority of Ireland (SEAI). National Heat Study: Low Carbon Gases for Heat - Potential, Costs and Deployment Options in Ireland. Technical report, February 2022. URL https://www.seai.ie/publications/Low-Carbon-Gases-for-Heat.pdf.

Teagasc. Mitigation - Marginal Abatement Cost Curve. Technical report, 2023. URL https://www.teagasc.ie/environment/climate-action/climate-centre/marginal-abatement-cost-curve-2023/mitigation/.

Teagasc. Dairy - Statistics point to stabilisation of national dairy cow numbers, February 2024. URL https://www.teagasc.ie/news--events/daily/dairy/Statistics-point-to-stabilisation-of-national-dairy-cow-numbers.php.

Teagasc. Teagasc National Farm Survey 2024 - Final Results. Technical report, Teagasc, October 2025.

Teagasc Greenhouse Gas Working Group. An Analysis of Abatement Potential of Greenhouse Gas Emissions in Irish Agriculture 2021-2030. Technical report, March 2019.

Sofia Tisocco, Ciara Beausang, Xinmin Zhan, and Paul 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. *Resources, Conservation and Recycling*, 206:107650, July 2024. ISSN 09213449. doi: 10.1016/j.resconrec.2024.107650. URL https://linkinghub.elsevier.com/retrieve/pii/S0921344924002441.

Trading Economics. EU Natural Gas TTF - Price - Chart - Historical Data - News. URL https://tradingeconomics.com/commodity/eu-natural-gas.

Trading Economics. EU Carbon Permits, March 2025. URL https://tradingeconomics.com/commodity/carbon.

Ian Vázquez-Rowe, Antonino Marvuglia, Sameer Rege, and Enrico Benetto. Applying consequential LCA to support energy policy: Land use change effects of bioenergy production. *Science of The Total Environment*, 472:78–89, February 2014. ISSN 0048-9697. doi: 10.1016/j.scitotenv.2013.10.097. URL https://www.sciencedirect.com/science/article/pii/S0048969713012412.

David M. Wall, Padraig O'Kiely, and Jerry D. Murphy. The potential for biomethane from grass and slurry to satisfy renewable energy targets. *Bioresource Technology*, 149:425–431, December 2013. ISSN 0960-8524. doi: 10.1016/j.biortech.2013.09.094. URL https://www.sciencedirect.com/science/article/pii/S0960852413015265.

David M. Wall, Eoin Allen, Barbara Straccialini, Padraig O'Kiely, and Jerry D. Murphy. Optimisation of digester performance with increasing organic loading rate for mono- and co-digestion of grass silage and dairy slurry. *Bioresource Technology*, 173:422–428, December 2014. ISSN 09608524. doi: 10.1016/j.biortech.2014.09.126. URL https://linkinghub.elsevier.com/retrieve/pii/S0960852414013856.

Benteng Wu, Richen Lin, Archishman Bose, Jorge Diaz Huerta, Xihui Kang, Chen Deng, and Jerry D. Murphy. Economic and environmental viability of biofuel production from organic wastes: A pathway towards competitive carbon neutrality. *Energy*, 285:129322, December 2023. ISSN 0360-5442. doi: 10.1016/j.energy.2023.129322. URL https://www.sciencedirect.com/science/article/pii/S0360544223027160.

Tong Zhu, John Curtis, and Matthew Clancy. Promoting agricultural biogas and biomethane production: Lessons from cross-country studies. *Renewable and Sustainable Energy Reviews*, 114:109332, October 2019. ISSN 1364-0321. doi: 10.1016/j.rser.2019.109332. URL https://www.sciencedirect.com/science/article/pii/S1364032119305404.

Dónal Ó Céileachair, Richard O'Shea, Jerry D. Murphy, and David M. Wall. Alternative energy management strategies for large industry in non-gas-grid regions using on-farm biomethane. *Applied Energy*, 303:117627, December 2021. ISSN 0306-2619. doi: 10.1016/j.apenergy.2021.117627. URL https://www.sciencedirect.com/science/article/pii/S0306261921009958.

Dónal Ó Céileachair, Richard O'Shea, Jerry D. Murphy, and David M. Wall. The effect of seasonal biomass availability and energy demand on the operation of an on-farm biomethane plant. *Journal of Cleaner Production*, 368:133129, September 2022. ISSN 0959-6526. doi: 10.1016/j.jclepro.2022.133129. URL https://www.sciencedirect.com/science/article/pii/S0959652622027184.