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National University of Ireland, Cork

Economic, environmental, and technical assessment of on-farm anaerobic digestion systems in Ireland.

Thesis presented by

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for the degree of

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University College Cork

Civil, Structural and Environmental Engineering

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Declaration

This is to certify that the work I am submitting is my own and has not been submitted for another degree, either at University College Cork or elsewhere. All external references and sources are clearly acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism and intellectual property.

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Date:

Acknowledgements

I dedicate this thesis to my family and all the people in my life that supported me and gave me the hope I needed to carry on in this endeavour.

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Abstract

Ireland's pursuit of producing 5.7 TWh of biomethane from anaerobic digestion (AD) plants, to reduce reliance on fossil-derived natural gas, necessitates a thorough examination of viable system configurations. The implementation of AD in Ireland is seen as a targeted approach to achieving emissions reduction of 25% in the agricultural sector. On-farm AD unlocks the opportunity to generate biomethane from indigenous feedstock and curtail emissions from livestock farming. Previous assessments of the mitigation potential of AD systems in agriculture have been undertaken through Marginal Abatement Cost Curves in an Irish context. Although this initial assessment deemed AD as a high-cost of abatement solution, recent uncertainty in energy prices, due to recent geopolitical events, might provide new opportunities for the development of biomethane from on-farm AD. Furthermore, using single values for abatement costs may not encompass or describe the impact of the varying system boundary of an AD system, which can have consequences for the financial and environmental performance. Such variables include the scale of the on-farm AD system, the feedstock used, and the biogas energy end-use. AD systems can vary significantly in terms of scale, design, technology, feedstock, and function.

This thesis delves into the financial and environmental viability of on-farm AD systems, emphasising the need to consider additional inputs and outputs beyond energy sales that lie within the system boundary. The work evaluates different biogas end-use options and varying farm sizes for on-farm AD systems, revealing a wide range of abatement costs, whilst accounting for the uncertainty of external factors.

The findings indicate that, when income from co-products such as biofertilisers are factored into the analysis, as well as the emissions reductions from digestate use, a more optimistic evaluation of AD system viability is attained. Analysis across different scales and process configurations reveals varying mitigation potential, with abatement costs ranging from -7 € tCO_{2eq}^{-1} to +816 € tCO_{2eq}^{-1}. A key result of the analysis shows that, if a single input variable is changed within the system boundary, the financial and environmental performance of a system can be significantly changed. The efficiency of the AD process emerges as a key determinant, alongside farm conditions such as grass silage yield and synthetic fertiliser use. While heat and electricity production exhibit lower uncertainty, biomethane production faces challenges, necessitating additional incentives for small-scale AD uptake. Novel

approaches, such as the integration of microbial electrolysis cell (MEC) technologies, could present an opportunity to enhance small-scale upgrading feasibility, though capital constraints remain Connecting on-farm AD systems through pipelines to centralised upgrading facilities offers a promising alternative to the transportation of materials to a large centralised AD plant, or upgrading biogas at small individual plants, reducing investment requirements. Overall, this research provides insights into enhancing the economic and environmental feasibility of on-farm AD systems, crucial for sustainable agricultural practices and emission reduction goals. Through strategic integration and policy support, on-farm AD holds promise as a key contributor to decarbonisation efforts, offering diversified revenue streams for farmers and addressing emissions from the agricultural sector. Further research and policy development are essential to realise the full potential of on-farm AD in contributing to sustainable development and mitigating climate change impacts.

Thesis output

Chapters published as papers or currently under review in peer-reviewed journals for which I am principally responsible:

Chapter 3:

Diaz Huerta, J., O'Shea, R., Murphy, J.D., Wall, D.M., 2023. A perspective on methodologies and system boundaries to develop abatement cost for on-farm anaerobic digestion. Bioengineered, 14(1). https://doi.org/10.1080/21655979.2023.2245991.

Chapter 4:

Diaz Huerta, J., Bose, A., Wall, D.M., Murphy, J.D., O'Shea, R., 2023. Assessing the cost variability of emissions abatement in small-scale on-farm anaerobic digestion. DeCarbon 1, 100008. https://doi.org/10.1016/J.DECARB.2023.100008

Additional outputs of the thesis include:

Co-authored papers:

Wu, B., Lin, R., Bose, A., Huerta, J. D., Kang, X., Deng, C., & Murphy, J. D., 2023. Economic and environmental viability of biofuel production from organic wastes: A pathway towards competitive carbon neutrality. Energy, 285, 129322. https://doi.org/10.1016/j.energy.2023.129322

Conference Outputs:

Oral presentation at Environ 2021, "Healthy Planet, Healthy Communities" Environmental Research Institute (Online, 16th-18th June 2021):

Integrating sensitivity and uncertainty analysis in the development of Marginal Abatement Cost Curves (MACC) for anaerobic digestion systems in Ireland.

Jorge Diaz Huerta[1], Richard O'Shea[1], David Wall[1], Jerry Murphy[1]

[1] MaREI Centre, Environmental Research Institute, University College Cork, Cork

Oral presentation at Environ 2022 "Unlocking Sustainability" Ulster University, Belfast, U.K. (20th -22th June 2022):

Marginal abatement cost curves for biogas in Ireland: Assessing on-farm anaerobic digestion through the use of an enviro-economic calculation tool.

Jorge Diaz Huerta[1], Richard O'Shea[1], David Wall[1], Jerry Murphy[1]

[1] MaREI Centre, Environmental Research Institute, University College Cork, Cork

Poster Presentation at 4th International Conference for Bioresource Technology for Bioenergy, Bioproducts & Environmental Sustainability, Lake Garda, Italy (14th-17th May 2023):

Development of a combined technoeconomic analysis and life-cycle analysis tool for calculating the carbon abatement cost of on-farm anaerobic digestion systems.

Jorge Diaz Huerta[1], Richard O'Shea[1], David Wall[1], Jerry Murphy[1]

[1] MaREI Centre, Environmental Research Institute, University College Cork, Cork

Poster Award Winner.

Contribution to papers

Chapter 3:

I was the first author of the paper. I was responsible for the data collection, processing, analysis, and interpretation of results. I carried out an analysis on the methodology and system boundary for developing abatement costs for an on-farm anaerobic digestion systems at different scales.

Chapter 4:

I was the first author of the paper. I developed an enviro-economic Excel tool to evaluate different biogas end-uses for on-farm anaerobic digestion systems at different scales. I undertook the data analysis and interpretation of results.

Chapter 5:

I was the author of the chapter. I was responsible for incorporating a Monte Carlo approach to the enviro-economic tool to integrate uncertainty modelling to assess on-farm AD systems. With the results I developed probability charts to illustrate the uncertainty associated with the abatement cost and abatement potentials for 16 different scenarios of on-farm AD systems.

Chapter 6:

I am the author of the chapter. I was responsible for collecting the data, and processing, analysing and interpreting the results. I adapted the results of my colleagues working within the same project (EcoAD) to examine the overall economic impact to incorporate novel technologies to on-farm AD and the overall cost for biogas logistics. I adapted the enviro-economic tool to compare the economic performance of microbial electrolysis cell (MEC) in AD against baseline (conventional) AD systems. Furthermore, I calculated the overall network cost to install biogas pipelines based on pipeline material cost previously calculated for an optimised pipeline layout.

Nomenclature

AD	Anaerobic digestion
BMP	Biomethane potential
CAP	Climate action plan
CAPEX	Capital Expenditure
CH_4	Methane
CHP	Combined heat and power
CNG	Compressed natural gas
CH_4	Methane
CO_2	Carbon dioxide
CO_{2eq}	Carbon Dioxide Equivalent
CSTR	Continuously stirred tank reactor
DM	Dry matter
DS	Dry solids
EU	European Union
FFC	Fossil fuel comparator
FIT	Feed-in-Tariffs
GBP	British Pound Sterling
GHG	Greenhouse gas
GJ	Gigajoule
GNI	Gas Networks Ireland
GWh	Gigawatt - hour
IQR	Interquartile Range
ILCD	International Reference Life Cycle Data System
IRR	Internal Rate of Return
kWe	Kilowatt-electric
kWth	Kilowatt-thermal
kWh	Kilowatt-hour
LCA	Life-Cycle Assessment
LCOE	Levelised Cost of Energy
MACC	Marginal Abatement Cost Curve
MCDA	Multi-criteria decision analysis
MJ	Megajoule

MST	Minimum spanning tree
MW	Megawatt
MWh	Megawatt hour
N_2O	Nitrous Oxide
OLR	Organic loading rate
OPEX	Operational expenditure
PJ	Petajoule
PSA	Pressure-swing absorption
RED	Renewable energy directive
RESS	Renewable energy sustainable support
RHI	Renewable heat incentive
SSRH	Support Scheme for Renewable Heat
SMY	Specific methane yield
tDM	Tonnes of Dry Matter
tFW	Tonnes of Fresh Weight
TEA	Techno-Economic Assessment
TS	Total solids
TWh	Terawatt hour
VS	Volatile solids

1 Introduction

1.1 Background to thesis

The European Union (EU), as part of its long-term strategy, has set out to achieve carbon neutrality by 2050, to address the increasing threat of global warming (1). This commitment has been further extended with the signing of the Glasgow Climate Pact at COP26, where 197 participating countries committed to further reductions of greenhouse gas (GHG) emissions and increased investments in decarbonisation technologies (2). Many countries have individually set their own national strategies to tackle rising GHG emissions as a result of the rapid post SARS-Cov-2 (Covid-19) pandemic economic growth, which increased the demand for fossil fuels and caused emissions to rise across the globe (3). In Ireland, the Climate Action Plan (CAP) serves as a response by the government to mitigate emissions across diverse sectors. However, sectors like agriculture pose unique challenges, due to intertwined economic and social considerations.

The agricultural sector in Ireland is one of the main contributors to the country's economic growth output accounting for 6% of the Gross National Income and 60% of agri-food products exports in 2020 (4). The primary agricultural outputs are dairy (milk) and livestock (beef) products that are produced on ca. 140,000 farms, with average farm size of around 32.5 hectares (5). Perennial ryegrass is cultivated for pasture on about 52% of Irish farms, and approximately 24% of these farms produce grass silage (6). Sources of GHG emissions on a farm are typically from livestock (enteric fermentation and manure management) and from the application of organic and synthetic fertiliser in the form of methane (CH_4) and nitrous oxide (N_2O), respectively (6).

Agriculture accounted for 33.3% of Ireland's GHG emissions in 2021, a slight reduction from 34% in 2020 (7). In 2022, agricultural emissions increased to 38.5% mainly from the use of nitrogen fertiliser and from emissions related to manure management (8). Consequently, Irish agriculture faces a significant decarbonisation challenge for this sector that requires careful planning to achieve the 2023 CAP goal of a 51% reduction in GHG emissions by 2030 (7). As part of these efforts to reduce emissions, the Irish government established specific sub-targets to be achieved by 2030. These include attaining an 80% share of renewable energy in the electricity sector, reducing the emissions in the electricity sector by 75%, a 50% reduction in emissions in the transport sector, and a 25% reduction in emissions in the agriculture sector (9). On-farm anaerobic digestion (AD) can offer a potentially viable pathway towards a sustainable agricultural sector by processing agricultural waste, including slurry, directly on-site, reducing the overall fugitive emissions from current slurry management practices, whilst producing renewable energy in the form of biogas and a nutrient-rich biofertiliser (digestate). However, the integration of on-farm AD must be assessed in terms of contributing to both environmental and energy-related objectives in the agricultural sector.

Biogas is generated through the decomposition of organic matter in the AD process and consists predominantly of methane (50 to $60\%_{vol}$) and carbon dioxide (40 to 50%). Through the removal of carbon dioxide, the biogas can be upgraded to produce biomethane (>97% methane). This biomethane can serve as a direct substitute for natural gas by injecting it to the national gas grid infrastructure. Additionally, it can be used as a transport fuel by utilising compressed natural gas (CNG) refuelling points. In line with the CAP, the biomethane sector was explored as a viable option for carbon abatement in the agriculture, transport, and energy sectors. To reach the abatement targets, the construction of up to 200 new AD plants by 2030 may be necessary, with an estimated annual production of 5.7 TWh of biomethane (7). However, ensuring the economic viability of these AD plants is crucial to overcome adoption challenges and successfully implement this technology on farms.

The assessment of the economic viability and performance of on-farm AD systems in Ireland will be essential to develop the biomethane sector. Previous assessments of this economic viability were conducted as part of the 2019 CAP, where two alternative applications of AD were examined for climate mitigation in the agriculture and forestry sectors. The applications involved the use of biogas for heat and electricity generation, as well as producing renewable heat from biomethane (10). However, both options were regarded as costly approaches to emissions reduction at that time and were represented by singular marginal abatement cost values associated with individual scenarios. These scenarios may not capture the diverse application of AD systems which include for variable technology, scale, design, feedstock, and function.

A techno-economic assessment (TEA) can be conducted to assess the technical and financial viability of the different configurations of AD systems. Such evaluations allow for a comparison and selection of the most optimal system configuration that can be deployed to Irish farms. Using a life-cycle assessment (LCA), the environmental sustainability can be assessed through the sub-category of climate change to evaluate the GHG emissions generated by the system. In coupling the economic (TEA) and environmental (LCA) outcomes, the cost and potential carbon abatement of a technology such as AD can be calculated in an Irish context. Furthermore such analysis can assess the potential for more novel technologies that may improve the performance of on-farm AD or refine and optimise the logistics of generating and supplying biogas to energy users. This thesis seeks to investigate the potential for AD on Irish farms to act as a strategic technology that can aid Ireland's decarbonisation objectives in the coming years.

1.2 Aims and objectives.

The specific aims and objectives of this thesis are:

i. Identify economic and environmental parameters to evaluate within the system boundary of an on-farm AD system.
ii. Determine the mitigation potential of on-farm AD systems at different scales.
iii. Develop a tool capable of assessing the economic and environmental performance of on-farm AD systems based on biogas end-uses.
iv. Generate an abatement cost curve for different configurations of on-farm AD systems at various scales based on biogas end-uses.
v. Determine the key economic and environmental parameters that impact the economic viability of on-farm AD systems.
vi. Assess the uncertainty associated with abatement costs and potential of on-farm AD to determine if additional sources of income are required to integrate on-farm AD systems to Irish farms.
vii. Assess the economic feasibility of integrating novel technologies such as microbial electrolysis cell in AD plants.
viii. Assess different strategies for integrating biogas pipelines in AD plants.

1.3 Thesis outline and link between chapters

This thesis is comprised of 7 chapters and additional appendices. The theme of each chapter relates to the assessment of the feasibility of on-farm anaerobic digestion systems in Ireland based on their technical, financial, and environmental performance. Chapter 2 consists of a literature review of the current state of the art regarding anaerobic digestion in Ireland, highlighting the current development of the biogas industry and the financial and technical challenges in integrating AD on Irish farms. Chapter 3 discusses the methodologies used to assess the economic and environmental feasibility of on-farm anaerobic digestion through the calculation of the abatement cost. Chapters 4 and 5 discuss the viability of on-farm anaerobic digestion systems based on four different biogas end-uses. Chapter 6 discusses the integration of novel AD technologies and the cost of using biogas pipelines to deliver biogas. Chapter 3 and 4 are peer-review journal papers, and their methodology, results and discussion were included in the thesis as per published manuscripts. Chapter 5 is ready to be submitted for review to a journal. Chapter 6 accounts for recent innovations in deploying AD at small-scale and concludes the work of the EcoAD project. Chapter 7 is a concluding chapter that includes recommendations for future research based on the findings of this thesis. The chapters of the thesis follow the academic paper model and are arranged as individual published journal papers that can be read individually, or as part of a whole. A summary of each chapter is detailed below.

Chapter 2: *Economic structure of on-farm anaerobic digestion to produce biogas: types of feedstocks, plant types, and biogas end-uses.*

This chapter outlines the literature review of the economic structure of on-farm anaerobic digestion conducted for this thesis. It encompasses the different types of on-farm agricultural feedstocks, the general structure, and system boundaries of on-farm AD plants, as well as the overall utilisation of the biogas produced by these plants. The overall economic outlook of AD in Ireland is discussed in relation to previous techno-economic analyses. Furthermore, it explores the levelised cost of abatement, abatement potential, and main economic and policy barriers.

Chapter 3: *A perspective on methodologies and system boundaries to develop abatement cost for on-farm anaerobic digestion.*

This chapter provides an overview of the use of marginal abatement cost to evaluate the greenhouse gas mitigation potential of AD in Ireland's agricultural sector. Previous studies have evaluated the use of large AD facilities but have deemed them high-cost abatement solutions. To compare abatement costs across different scales, two case studies of on-farm AD systems, representing small and medium scales, were analysed. The abatement costs ranged between -117 to +79 € per t CO_{2eq}, depending on various factors such as the overall revenue streams, cost and emissions savings considered within the system boundary. The addition of key variables such as biofertiliser sales, displaced energy savings, additional incentives, and emission savings from the avoided use of fertiliser were found to lower the overall abatement cost of the systems. Furthermore, as methodologies, system boundaries, and assumptions vary between studies, assigning a single mitigation cost to a technology such as AD might not be representative of the overall financial viability and environmental mitigation these systems can achieve.

Chapter 4: *Assessing the cost variability of emissions abatement in small-scale on-farm anaerobic digestion.*

This chapter evaluates the economic performance of different biogas end-uses for on-farm AD systems across Ireland. These systems can vary in scale, design, technology, and feedstock, leading to differing abatement costs and potentials. To determine the most economically feasible scenarios for Ireland, a comparative analysis was conducted across different system configurations and farm sizes. Each farm size was assessed with four different biogas end-use configurations, comprising heat generation, electricity generation, biomethane production, and biomethane production using renewable energy sources, resulting in a total of sixteen scenarios. Additionally, changes in single input variables within each configuration's system boundary were applied to evaluate their impact on the financial and environmental performance of the system.

Chapter 5: *Probabilistic analysis of variables affecting the abatement cost of on-farm anaerobic digestion in Ireland.*

This chapter models the impact of external events on the calculation of abatement costs for on-farm AD systems in Ireland. A Monte Carlo approach was employed to conduct an uncertainty analysis comparing the system viability of each of the sixteen scenarios evaluated in Chapter 4. The analysis considered input variables affecting farm conditions, operational parameters of the digester, and economic assumptions such as revenues and costs for each scenario. 10,000 simulations were conducted for each scenario, and the outcomes were presented as probability charts to illustrate the uncertainty associated with abatement costs and potential. Furthermore, the overall uncertainty associated with each scenario was used to determine if additional incentives were required for a biogas end-use configuration to be financially competitive.

Chapter 6: *Investigating the economic impact of novel technologies and biogas logistics for on-farm anaerobic digestion.*

This chapter assesses the potential improvement achieved by integrating novel technologies into the baseline on-farm AD systems and examines the overall cost associated with transporting biogas via pipelines. The microbial-electrolysis cell (MEC) was evaluated as a novel technology capable of enhancing the efficiency of conventional AD systems by improving biogas and biomethane production. While MEC-AD systems have been evaluated at laboratory scale, their application at the large scale has yet to be explored. A farm-scale scenario was modelled to compare the impact of integrating the MEC-AD system on the four biogas end-use configurations evaluated in Chapter 4. Additionally, an assessment of the overall network cost to deliver biogas from 10 AD plants to a single biogas user was conducted. The economic evaluation considered two scenarios: one where each farm had its own upgrading system and supplies biomethane to a central grid injection point for transportation optimisation, and another where each plant supplies biogas to a centralised upgrading plant with an equivalent biogas demand.

Chapter 7: *Conclusions and recommendations.*

This chapter offers conclusions for each of the eight objectives outlined in section 1.2. These conclusions are drawn in consideration of the SFI MaREI research centre's three impact priorities, which include informing policy, supporting industry, and empowering society. Additionally, recommendations for future research are provided, focusing on the comprehensive assessment of on-farm AD systems.

References

1. European Commission. 2050 long-term strategy [Internet]. 2016. Available from: https://ec.europa.eu/clima/policies/strategies/2050_en

2. UN and UNFCCC. 'The Glasgow Climate Pact', in 2021 United Nations Climate Change Conference [Internet]. Glasgow; [cited 2023 Jun 17]. Available from: https://webarchive.nationalarchives.gov.uk/ukgwa/20230401054904/https://ukcop26.org/cop26-presidency-outcomes-the-climate-pact/

3. IEA. World Energy Outlook 2022 [Internet]. 2022 [cited 2023 Jun 17]. Available from: https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf.

4. Government of Ireland. Agri-Food and the Economy [Internet]. 2021 [cited 2023 May 30]. Available from: https://www.gov.ie/en/publication/e2273-agri-food-and-the-economy/

5. Sustainable Food SI. Agriculture & Food in Ireland [Internet]. [cited 2022 Apr 19]. Available from: https://www.sfsi.ie/agriculture-food-ireland/

6. KPMG, Devenish, Gas Networks Ireland. Sustainability of Biomethane Production in Ireland Exploring how Ireland can deliver a sustainable, agriculture-led biomethane industry [Internet]. 2021 [cited 2022 Jul 21]. Available from: https://www.gasnetworks.ie/biomethane-sustainability-report-2021.pdf

7. Government of Ireland. Climate Action Plan 2023 [Internet]. 2023 [cited 2023 May 2]. Available from: https://www.gov.ie/en/publication/7bd8c-climate-action-plan-2023/

8. Agriculture | Environmental Protection Agency [Internet]. [cited 2022 Oct 26]. Available from: https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/agriculture/

9. Government of Ireland. Sectoral Emissions Ceilings [Internet]. [cited 2023 Jun 28]. Available from: https://www.gov.ie/en/publication/76864-sectoral-emissions-ceilings/

10. Government of Ireland. Climate Action Plan 2019 [Internet]. 2019 [cited 2022 Jul 13]. Available from: https://www.gov.ie/en/publication/ccb2e0-the-climate-action-plan-2019/

2 Economic structure of on-farm anaerobic digestion to produce biogas: types of feedstocks, plant types, and biogas end-uses

2.1 Overview of Ireland’s agricultural sector and feedstock availability

Since 2011, there has been a notable increase in the number of anaerobic digestion (AD) plants across Europe, aimed at producing biogas and biomethane as an alternative to fossil-derived natural gas. In 2020, biomethane production in Europe accounted for 17% (32 TWh) of the total biogas production of 191 TWh (1). In contrast, the development of the AD industry in Ireland has been limited, with only 59 AD plants as of 2018. Among these, only 3 AD plants produce biomethane, resulting in a combined annual production of 22.8 GWh (2). As part of the European Union (EU), Ireland is required to achieve a 32% share of renewable energy by 2030 as set in the Renewable Energy Directive (RED) (3). This target is further divided into three sub-targets that include achieving: 70% renewable electricity (RES-E), 13.4% renewable energy in transport (RES-T), and 24% renewable heating and cooling (RES-H&C) (4). As of 2018, Ireland has greatly progressed in the RES-E (33.2%) and RES-T (7.2%) leaving only RES-H&C (6.5%) as one of the tougher targets to achieve (4). A previous study by *O’Shea et al.* (5) assessed the potential of biomethane production from grass silage and cattle slurry, considering the abundant resources available in the agricultural sector. The study estimated that grass silage could potentially generate 128.4 PJ a^{-1} of biomethane, and cattle slurry could contribute 9.6 PJ a^{-1} (5). Given that Ireland's heat demand in 2019 was 200 PJ, this indicates that biomethane production from these sources could meet approximately 69% of the total heat energy requirements (6).

2.1.1 Agricultural practices and availability of slurry resources

Grass-based agriculture is the primary focus of Irish farming in which most of the agricultural area is devoted to growing grass (silage, hay, and pasture) and a small area is devoted to cereals and other crop productions (7). This intensive production of grass thrives in temperate maritime/oceanic climates of island countries, such as in the cases of Ireland and New Zealand (8). In Ireland, farming practices for dairy production prefer the use of pasture-based systems in which the livestock are outdoor grazing, as shown in the range of dairy cows that had pasture access for grazing which was between 95 to 100% in 2019 (9). Pasture-based systems are particularly valued as these improve livestock welfare while improving the economic and environmental sustainability of milk production (10,11). Most of the outdoor grazing takes place during summer, and during winter the livestock is housed indoors in which slurry can be collected underneath slatted-floor facilities (12). Based on the farm location, the amount of time indoors can range between 16 to 22 weeks, depending on the required minimum storage capacity set for the region (13). Taking into consideration Ireland's 6.5 million cattle population, which accounts for 1.5 million dairy cows, there is a considerable quantity of slurry available as feedstock (14). Based on previous estimations by *Wall et al.* (15), the annual production of dairy slurry in Ireland could amount to more than 7 Mt, which is typically spread to land in raw form, which could be instead used as feedstock for AD.

Dairy slurry has been widely reported as feedstock for AD with an approximate dry solid (DS) content between 5.7% to 9.6%, and a volatile solids (VS) content between 5.1% to 6.8% (15–17). These properties can vary seasonally, depending on factors such as the animal's diet and lactation stage (17). Further research has also been conducted to assess the potential methane yields of the substrate based on results from biochemical methane potential (BMP) assays, which yields ranged between 136 to 239 L CH_4 $kgVS^{-1}$ (15,17). However, it has been found that the use of slurry alone might yield low methane production for AD, due its lower biodegradation rates (15,16). That said, its inclusion on the AD process can reduce the overall emissions from manure management, which facilitates the progression towards a more sustainable agricultural sector (18). Furthermore, it provides a source of renewable energy for the farm while reducing water, soil, and air pollution from its use as fertiliser (18).

2.1.2 Grass silage utilisation and availability as feedstock for AD.

A significant portion of agricultural farming in Ireland is dedicated to grass production. In 2019, agricultural land accounted for a total of 4.52 million hectares (ha), of which 92% was directed to growing grass, and from this around 1.1 million ha was directed to produce grass silage (19). This feedstock has been found to be a suitable energy crop produced from agricultural biomass for countries such as Finland and Germany (2). For Ireland, it has been found that the grass silage surplus to livestock requirements could provide an ideal source of biomass for its use in AD (15,20). However, the cost of grass production needs to be sustainable to be considered as a viable option for AD.

Farmers in Ireland are confronted with the dual challenge of optimising silage yield while simultaneously achieving target silage quality for their production systems.

Grass yield can vary depending on the region within Ireland, typically ranging from 7 to 9 tDM per ha per annum (ha^{-1} a^{-1}) (21). However, through enhancements in nitrogen fertiliser application and the implementation of improved grass utilisation practices on fertile farmlands, yields of up to 11 to 13 tDM ha^{-1} a^{-1} can be achieved (22–26). To assist farmers in achieving high levels of grass growth at a low cost, Teagasc (Agriculture and Food Development Authority) launched the "Grass 10" campaign, aiming to reach a target of 10 tDM ha^{-1} a^{-1} of grass grown across Ireland by providing guidance on soil fertility, sward composition, and grassland management decisions (27). Given that 85% of farms already produce silage annually (28), the use of silage presents an excellent source of feedstock for biomethane compared to rapeseed and wheat, as there is no need for changes to land use, annual ploughing and planting (26).

The potential for grass silage as feedstock in digestion systems has been widely reported with a DS content around 12% to 33% (17,26) and a VS content between 11% to 27% (15,17,26,29). The properties of grass silage may vary depending on the cultivation method used and the region from which it is sourced. Previous BMP assays have been conducted to evaluate methane yield at mesophilic temperatures (35°C) from the mono-digestion of various grass species and types of grass silage. Methane yields were found to range between 253 to 432 L CH4 $kgVS^{-1}$ (17,30), depending on the maturity and harvest date of the feedstock. Biomass pretreatment technologies can also be employed on grass to increase methane yield by enhancing digestion efficiency. *Wall et al.* (31), have explored grass pretreatment methods such as the use of biological enzymes and particle size reduction. While these methods show promise, further investigation is needed to assess the associated costs of implementation.

2.2 System boundary of on-farm AD systems

2.2.1 Reactor types for AD systems

Various types of reactors systems and configurations can be used for AD plants. These are commonly classified based on the amount of feedstock they process, the quantity of gas they produce, or, whether additional energy conversion is implemented (32). In Ireland, reactors such as dry batch digesters or continuous stirred tank reactors (CSTR) have been recommended for the mono-digestion of grass (33). For slurries, such as dairy manure, swine manure and processing waste, with DS concentrations ranging between 3 to 10%, CSTR reactors are also recommended, due to their ability to thoroughly mix the feedstock (34–36). Given that co-digestion of grass silage and dairy slurry has been proven to offer a more stable AD process (31), it is not surprising that these systems are commonly chosen for on-farm AD systems to co-digest slurry with other types of farm crops or wastes (37–39).

The general structure of the CSTR reactor comprises a circular insulated tank, constructed from reinforced concrete or steel, equipped with additional heating, and mixing capabilities (32). These reactors commonly incorporate a continuously stirred stage and may consist of one or more tanks or reactor vessels. Additionally, continuous reactors may adopt a two-phase configuration, where the solid substrate undergoes hydrolysis and acidogenesis initially, followed by the optimisation of conditions for methanogenesis in the second phase (40). Single stage CSTR systems often operate with high hydraulic retention times (HRT) (41,42), maintaining an average organic loading rate (ORL) between 2 to 4 kg VS m^{-3} d^{-1}, as a high ORL can lead to inhibition during the biogas production process (16,42,43).

CSTR systems can also be classified as low-rate systems since the feedstock needs to be held longer in the digester to maximize biogas yield (32). Typically, these systems operate the digestion process under mesophilic (25–40 °C) or thermophilic (50–65 °C) temperature conditions (34,36). For most on-farm AD systems, the mesophilic temperature range is commonly utilised as it can effectively degrade materials with the added benefit of lower energy consumption compared to thermophilic systems (44,45). However, if pasteurizing manure is required, due to a legal mandate for reducing pathogen levels, a thermophilic temperature range might be preferred (46).

2.2.2 Use of bioenergy and by-products of on-farm AD

For many on-farm AD systems installed in the EU and North America, the biogas produced is usually used to generate electricity and heat with the aid of a combined heat and power (CHP) unit (37,46,47). This electricity can be utilised for local consumption on the farm or exported to the grid (46). Another approach involves burning the biogas in boilers to fulfil the heat demand required in the farm or the dairy enterprise (46). However, considering the limited thermal demand from Irish farms, the potential heat generated from the biogas could instead be directed towards large industrial energy users seeking to reduce their carbon footprint (48). Another viable option for utilising the heat could be in local community heating schemes. In Ireland, this presents a potentially feasible option, given the presence of around 18,641 small areas with the potential for district heating installation (49).

Biogas can also be upgraded to biomethane by removing carbon dioxide and increasing the methane concentration to above 97% (50). This enhancement in the energy density of the gas enables its use as a substitute for vehicle fuel or injection into the gas grid, making it suitable for appliances designed for natural gas use (46). Furthermore, when compared to other fuels like diesel or heavy fuel oil, biomethane presents lower sulphur content and reduced life cycle greenhouse gas emissions (51). Various technologies are available for biogas upgrading in the market, including pressure swing adsorption, amine scrubbing, membrane technologies, and water scrubbing (50). While, in most cases, small-scale upgrading might not be financially viable, small upgrading plants do exist, albeit typically involving high investment and maintenance costs (32). Upgrading is commonly considered for farms with high biogas production rates, which can exceed 300 m^3 h^{-1} (46).

AD as a mitigation technology offers additional benefits to a farm such as generation of a nutrient-rich biofertiliser (digestate), the reduction of odours and the reduction of pathogen loads by reducing raw slurry application to land (52). Different technological solutions can also be applied to AD plants to recover waste heat generated during the process to generate on-site renewable energy (53). Previous studies have explored the environmental benefits of integrating AD with farms, where, reductions of 32% to 44% (CO_{2eq}) were reported for gases such as methane and nitrogen oxides (54,55). Digestate use as a biofertiliser has the potential to increase soil fertility, although this can be dependent on the type of feedstock used (56,57). Furthermore, the displacement of chemical and raw slurry fertilisers through the application of digestate as an organic biofertiliser enables the farmer to shift towards a more sustainable agricultural practice. Fugitive methane emissions from open slurry tanks can be negated by capturing the methane generated (58). The amount of water consumption, energy, and greenhouse gas (GHG) emissions avoided from reduced chemical fertiliser use can be considered a significant benefit (59).

2.3 Economic outlook of AD in Europe and Ireland

Considering the environmental climate-related challenges ahead (60), and the EU goal to achieve climate neutrality by 2050 (61), the European Commission launched

“The Green New Deal” in 2019 (62). This deal encompasses key policies and measures that should be incorporated into circular economy action plans to encourage member states to meet the climate objectives for 2030 and 2050 (62). Circular economy plans involve initiatives that prompt national authorities to establish monitoring frameworks, facilitating progress towards a circular economy to achieve the EU’s climate neutrality target (63). These plans also aim to identify best practices and the corresponding policies necessary for their implementation. One of the strategies included in the deal is the "Farm to Fork" strategy, which aims to make food systems environmentally friendly, as they account for one-third of global GHG emissions (63). The Farm to Fork strategy aims to redesign agri-food systems to help farmers to transition to sustainable agriculture practices through advisory services, eco-schemes, and agri-environment-climate measures and investments (64). AD systems can be a key part for Irish farms to align with a circular economy approach as well as the "Farm to Fork" targets of the EU. Utilising digestate as a primary component to manufacture organic biofertiliser instead of chemical fertilisers further supports these goals. Additionally, it avoids emissions associated with chemical fertiliser production.

The number of AD plants (and subsequently biogas and biomethane production) has increased substantially across Europe with the aim of reducing fossil-derived natural gas dependency (55). This rise will continue as targets are set to produce 35 billion cubic meters of biomethane by 2030 (65). In Ireland, the uptake for this technology remains very low in comparison to other European countries. This can primarily be associated with the level of uncertainty such systems present to farmers in terms of financial return (52). Two of the most common feedstocks for on-farm AD systems in Ireland are grass silage and cattle slurry. The production of grass surplus to livestock requirements is a key feedstock for biogas production (26). However, to achieve the successful implementation of on-farm AD systems, proof of its economic viability is imperative to overcome the potential obstacles in the adoption of the technology.

2.3.1 Previous techno-economic analysis of on-farm AD in Ireland

To successfully implement AD projects an accurate assessment of the economic viability which takes into consideration the ever-changing process characteristics is required. Techno-economic assessments (TEAs) can determine the potential technical and financial performance and the overall feasibility of projects. Such models consist primarily of mass and energy balances of the proposed system with the financial data related to the cost and revenues generated during the lifetime of the project (66). Scenario-type analyses within a TEA allow for a high-level assessment of the variation and feasibility of AD plants using sensitivity analysis. Previous TEAs for AD facilities in Ireland have focused primarily on large centralised anaerobic digestion facilities (67–72). It was found that the production of biomethane from organic materials such as the organic fraction of municipal solid waste and slaughterhouse waste can be economically feasible and competitive. Small-scale digesters are less accounted for in Ireland and have only previously been assessed in two studies for pig farms (73,74) and a single study for a dairy farm (75). In general, there is a lack of TEA data for small-scale on-farm AD systems.

2.3.2 Life cycle assessment and abatement cost curves

An economic analysis can be coupled with a Life-Cycle Assessment (LCA) to compare and analyse the impact of different technologies and products on the environment based on the carbon emissions generated or avoided during the entire life cycle of a process. The impact of the process can be analysed in terms of the inputs and outputs of the materials and the energy used in the process/product life cycle (76). A critical aspect for the development of an LCA is the definition of the boundary for the analysis (77). Based on the inputs and outputs selected, different system boundaries can be drawn, each one leading to different results and a multitude of scenarios. Biogas needs to be considered a zero-carbon renewable fuel; therefore, AD plants are required to adhere to the sustainability criteria outlined by the Renewable Energy Directive II (RED II) (78). Overall, the emissions generated during the production of biogas from agricultural biomass must achieve at least an 80% emissions savings compared to a fossil fuel comparator when used for electricity and heating, or a 70% emissions savings when used for transport (78).

The result of both analyses (TEA and LCA) can be combined to measure the mitigation potential of a technology and compared to other technologies to provide a better understanding of the options available. An abatement cost curve can be a useful tool to evaluate the cost and abatement potential of various mitigation technologies. This curve orders the options based on the cost of GHG abatement of a measure and by the quantity of GHG emissions mitigated (79). Abatement measures are ranked based on the cost-effectiveness the technology provides in a specific sector, and the results of these rankings have been used by many governments to establish low carbon policies (80).

2.3.3 Economic and policy barriers

One of the main economic barriers that on-farm AD systems face in Ireland relates to the uncertainty associated with the total investment cost and the potential financial returns. This uncertainty is a common concern among farmers and stakeholders in the literature, especially regarding the economics of renewable energy projects (81,82). To overcome these economic barriers, many governments have introduced incentives to provide financial viability to early adopters and to promote the adoption of renewable energies (46,83). The government of Ireland has two different schemes to provide tariff support for projects that generate renewable energy. In the case of heat, the support scheme for renewable heat (SSRH) provides a tariff of 29.5 € MWh^{-1} of energy produced below the threshold of 1,000 MJ a^{-1} (84). For electricity, the renewable electricity support scheme (RESS) provided a tariff of 74.08 € MWh^{-1} through its first auction undertaken by the state transmission operators (85). Both schemes provide payments for a period of up to 15 years. These incentives provide a financial support system for on-farm AD systems that generate either heat and electricity from a CHP unit or a boiler.

For biomethane, historically, the price of production has been generally more expensive than fossil fuel, due the overall low cost of production of the fossil fuels and the costs associated with the construction of the required infrastructure to produce biomethane (86). Most European governments provide operational support through tariffs that ensure biomethane developers receive revenue for each unit of biomethane injected into the gas grid over a specified period (87). In recent times, more advanced auction mechanisms or obligation schemes to support biomethane development have been explored across Europe. To increase the development of biomethane in the Netherlands, a renewable gas obligation was introduced for the domestic gas sector (88). To promote the adoption in its industry, Denmark has assessed the use of biomethane obligations and auctions (88). For Ireland two schemes have been considered: to promote the decarbonisation of the heat sector the renewable heat obligation (RHO) scheme will be introduced; and for the transport sector the renewable transport fuel obligation (RTFO) will support the use of biomethane as transport fuel (89). Although, to successfully develop the biomethane industry in Ireland is required to evaluate which policies will provide the most cost-efficient pathway for AD plants.

The analysis of the economic and environmental feasibility of on-farm AD in Ireland comparing different plant types, farm sizes, and biogas end-uses is still limited in the literature. To assess the financial and the environmental viability of AD, different scenarios based on the available pathways for AD plants need to be explored, while also evaluating the GHG emissions generated in the production of biogas in a cost-effective way. Developing a tool that combines both financial and environmental analyses will facilitate the assessment of the variations AD systems can present and provide insight into the main cost drivers, required policy development, and future research needed to integrate on-farm AD into Irish farms. Overall, this thesis aims to present the context, challenges, and potential solutions related to decarbonising the agricultural sector in Ireland through on-farm AD.

References

1. Sulewski P, Ignaciuk W, Szymańska M, Wąs A. Development of the Biomethane Market in Europe. Energies 2023, Vol 16, Page 2001 [Internet]. 2023 Feb 17 [cited 2023 May 31];16(4):2001. Available from: https://www.mdpi.com/1996-1073/16/4/2001/htm

2. IEA Bioenergy Task 37. Country Report Summaries 2021 [Internet]. 2022 [cited 2023 May 31]. Available from: https://task37.ieabioenergy.com/country-reports

3. Government of Ireland. Climate Action Plan 2023 [Internet]. 2023 [cited 2023 May 2]. Available from: https://www.gov.ie/en/publication/7bd8c-climate-action-plan-2023/

4. Government of Ireland. Ireland's National Energy and Climate Plan 2021-2030 [Internet]. 2021 [cited 2023 Jul 3]. Available from: https://www.gov.ie/en/publication/0015c-irelands-national-energy-climate-plan-2021-2030/

5. O'Shea R, Wall DM, Kilgallon I, Browne JD, Murphy JD. Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region. Appl Energy [Internet]. 2017;188:237–56. Available from: http://www.sciencedirect.com/science/article/pii/S0306261916317524

6. SEAI. Energy in Ireland 2020 Report [Internet]. 2019 [cited 2023 Jul 20]. Available from: https://www.seai.ie/publications/Energy-in-Ireland-2020.pdf

7. Teagasc. Agriculture in Ireland - Teagasc | Agriculture and Food Development Authority [Internet]. 2023 [cited 2023 Jul 20]. Available from: https://www.teagasc.ie/rural-economy/rural-economy/agri-food-business/agriculture-in-ireland/

8. Markiewicz-Keszycka M, Carter A, O'brien D, Henchion M, Mooney S, Hynds P. Pro-environmental diversification of pasture-based dairy and beef production in Ireland, the United Kingdom and New Zealand: a scoping review of impacts and challenges. Renewable Agriculture and Food Systems [Internet]. 2023 Dec 21 [cited 2023 Jul 20];38:e5. Available from: https://www.cambridge.org/core/journals/renewable-agriculture-and-food-systems/article/proenvironmental-diversification-of-pasturebased-dairy-and-beef-production-in-ireland-the-united-kingdom-and-new-zealand-a-scoping-review-of-impacts-and-challenges/A9A7FC4B3E3A65C7F29DA9739DE392CB

9. van den Pol-van Dasselaar A, Hennessy D, Isselstein J. Grazing of Dairy Cows in Europe—An In-Depth Analysis Based on the Perception of Grassland Experts. Sustainability. 2020 Feb 4;12(3):1098.

10. Smid AMC, Weary DM, von Keyserlingk MAG. The Influence of Different Types of Outdoor Access on Dairy Cattle Behavior. Front Vet Sci. 2020 May 13;7.

11. Hennessy D, Delaby L, van den Pol-van Dasselaar A, Shalloo L. Increasing Grazing in Dairy Cow Milk Production Systems in Europe. Sustainability. 2020 Mar 20;12(6):2443.

12. Beausang C, McDonnell K, Murphy F. Assessing the environmental sustainability of grass silage and cattle slurry for biogas production. J Clean Prod. 2021 May 20;298:126838.

13. Hennessy T, Buckley C, Cushion M. teagasc. 2011 [cited 2022 Mar 10]. National farm survey of manure application and storage practices on Irish farms. Available from: https://www.teagasc.ie/media/website/publications/2011/TeagascNationalFarmSurveyOfManureApplication.pdf

14. CSO. Livestock Survey December 2022 [Internet]. 2022 [cited 2023 Jul 6]. Available from: https://www.cso.ie/en/releasesandpublications/ep/p-lsd/livestocksurveydecember2022/

15. Wall DM, O'Kiely P, Murphy JD. The potential for biomethane from grass and slurry to satisfy renewable energy targets. Bioresour Technol [Internet]. 2013 [cited 2022 Apr 21];149:425–31. Available from: https://pubmed.ncbi.nlm.nih.gov/24135566/

16. Wall DM, Allen E, Straccialini B, O'Kiely P, Murphy JD. Optimisation of digester performance with increasing organic loading rate for mono- and co-digestion of grass silage and dairy slurry. Bioresour Technol. 2014 Dec 1;173:422–8.

17. Allen E, Wall DM, Herrmann C, Murphy JD. A detailed assessment of resource of biomethane from first, second and third generation substrates. Renew Energy. 2016 Mar 1;87:656–65.

18. Manyi-Loh CE, Mamphweli SN, Meyer EL, Okoh AI, Makaka G, Simon M. Microbial Anaerobic Digestion (Bio-Digesters) as an Approach to the Decontamination of Animal Wastes in Pollution Control and the Generation of Renewable Energy. Int J Environ Res Public Health [Internet]. 2013;10(9):4390–417. Available from: https://www.mdpi.com/1660-4601/10/9/4390

19. CSO. Crops and Livestock Survey June Final 2019 [Internet]. 2020 [cited 2024 Apr 23]. Available from: https://www.cso.ie/en/releasesandpublications/er/clsjf/cropsandlivestocksurveyjunefinal2019/

20. Smyth BM, Smyth H, Murphy JD. Determining the regional potential for a grass biomethane industry. Appl Energy. 2011 Jun 1;88(6):2037–49.

21. McEniry J, Crosson P, Finneran E. JSTOR. 2013 [cited 2022 Nov 16]. How much grassland biomass is available in Ireland in excess of livestock requirements? Available from: https://www.jstor.org/stable/23631018

22. Murphy JD, Power NM. An argument for using biomethane generated from grass as a biofuel in Ireland. Biomass Bioenergy. 2009 Mar 1;33(3):504–12.

23. Meehan P, Burke B, Doyle D, Barth S, Finnan J. Exploring the potential of grass feedstock from marginal land in Ireland: Does marginal mean lower yield? Biomass Bioenergy. 2017 Dec 1;107:361–9.

24. Holen NM, Brereton AJ. Vol. 41, Irish Journal of Agricultural and Food Research. 2022 [cited 2022 Jun 14]. p. 213–26 An Assessment of the Potential Impact of Climate Change on Grass Yield in Ireland over the Next 100 Years on JSTOR. Available from: https://www.jstor.org/stable/25562465?seq=1

25. KPMG, Devenish, Gas Networks Ireland. Sustainability of Biomethane Production in Ireland Exploring how Ireland can deliver a sustainable, agriculture-led biomethane industry [Internet]. 2021 [cited 2022 Jul 21]. Available from: https://www.gasnetworks.ie/biomethane-sustainability-report-2021.pdf

26. Smyth BM, Murphy JD, O'Brien CM. What is the energy balance of grass biomethane in Ireland and other temperate northern European climates? Renewable and Sustainable Energy Reviews. 2009 Dec 1;13(9):2349–60.

27. Teagasc. Grass10 - Grassland Management [Internet]. 2023 [cited 2023 Sep 6]. Available from: https://www.teagasc.ie/crops/grassland/grass10/

28. Teagasc. Quality Grass Silage [Internet]. 2024 [cited 2024 Apr 25]. Available from: https://www.teagasc.ie/crops/grassland/quality-grass-silage/

29. FitzGerald JA, Wall DM, Jackson SA, Murphy JD, Dobson ADW. Trace element supplementation is associated with increases in fermenting bacteria in biogas mono-digestion of grass silage. Renew Energy. 2019 Aug;138:980–6.

30. Voelklein MA, Rusmanis D, Murphy JD. Increased loading rates and specific methane yields facilitated by digesting grass silage at thermophilic rather than mesophilic temperatures. Bioresour Technol. 2016 Sep;216:486–93.

31. Wall DM, Allen E, Straccialini B, O'Kiely P, Murphy JD. The effect of trace element addition to mono-digestion of grass silage at high organic loading rates. Bioresour Technol. 2014 Nov;172:349–55.

32. O'Connor S, Ehimen E, Pillai SC, Black A, Tormey D, Bartlett J. Biogas production from small-scale anaerobic digestion plants on European farms. Renewable and Sustainable Energy Reviews [Internet]. 2021;139:110580. Available from: https://www.sciencedirect.com/science/article/pii/S1364032120308649

33. Nizami AS, Thamsiriroj T, Singh A, Murphy JD. Role of Leaching and Hydrolysis in a Two-Phase Grass Digestion System. Energy & Fuels. 2010 Aug 19;24(8):4549–59.

34. Kougias PG, Angelidaki I. Biogas and its opportunities—A review. Front Environ Sci Eng. 2018 Jun 30;12(3):14.

35. AgSTAR. Project Development Handbook. A Handbook for Developing Anaerobic Digestion/Biogas Systems on Farms in the United States [Internet]. EPA; 2014. Available from: https://www.epa.gov/sites/production/files/2014-12/documents/agstar-handbook.pdf#page=81

36. Manager R, Krich K, Augenstein D, Batmale JP, Benemann J, Rutledge B, et al. Biomethane from Dairy Waste, a Sourcebook for the Production and Use of Renewable Natural Gas. 2005 [cited 2024 Apr 25]; Available from: https://escholarship.org/uc/item/35k1861z

37. Usack JG, Gerber Van Doren L, Posmanik R, Labatut RA, Tester JW, Angenent LT. An evaluation of anaerobic co-digestion implementation on New York State dairy farms using an environmental and economic life-cycle framework. Appl Energy. 2018 Feb;211:28–40.

38. Van Stappen F, Mathot M, Decruyenaere V, Loriers A, Delcour A, Planchon V, et al. Consequential environmental life cycle assessment of a farm-scale biogas plant. J Environ Manage. 2016 Jun;175:20–32.

39. Wilkinson KG, Wilkinson KG. Development of On-Farm Anaerobic Digestion. Biocycle [Internet]. 2011 Aug 23 [cited 2024 Apr 25];52(1):49–50. Available from: https://www.intechopen.com/chapters/17436

40. Janesch E, Pereira J, Neubauer P, Junne S. Phase Separation in Anaerobic Digestion: A Potential for Easier Process Combination? Frontiers in Chemical Engineering. 2021 Sep 1;3.

41. USDA. Beef Feedlot Industry Manual. The United States Department of Agriculture, Animal and Plant Health Inspection Service, Veterinary Services; 2011.

42. Tsegaye D, Khan MM, Leta S. Optimization of Operating Parameters for Two-Phase Anaerobic Digestion Treating Slaughterhouse Wastewater for Biogas Production: Focus on Hydrolytic–Acidogenic Phase. Sustainability. 2023 Mar 21;15(6):5544.

43. Jürgensen L, Ehimen EA, Born J, Holm-Nielsen JB. A combination anaerobic digestion scheme for biogas production from dairy effluent—CSTR and ABR, and biogas upgrading. Biomass Bioenergy. 2018 Apr;111:241–7.

44. Labatut RA, Angenent LT, Scott NR. Conventional mesophilic vs. thermophilic anaerobic digestion: A trade-off between performance and stability? Water Res. 2014 Apr 15;53:249–58.

45. Orozco AM, Nizami AS, Murphy JD, Groom E. Optimizing the thermophilic hydrolysis of grass silage in a two-phase anaerobic digestion system. Bioresour Technol. 2013 Sep;143:117–25.

46. Lukehurst C, Bywater A, Baxter D, Banks C. Exploring the viability of small scale anaerobic digesters in livestock farming. IEA Bioenergy [Internet]. 2015 [cited 2024 Apr 26]; Available from: https://task37.ieabioenergy.com/wp-content/uploads/sites/32/2022/02/Small_Scale_RZ_web2.pdf

47. Ahlberg-Eliasson K, Nadeau E, Levén L, Schnürer A. Production efficiency of Swedish farm-scale biogas plants. Biomass Bioenergy. 2017 Feb 1;97:27–37.

48. Ó Céileachair D, O'Shea R, Murphy JD, Wall DM. Alternative energy management strategies for large industry in non-gas-grid regions using on-farm biomethane. Appl Energy. 2021 Dec 1;303:117627.

49. Element Energy, Ricardo Energy and Environment. District Heating and Cooling National Heat Study Spatial Analysis of Infrastructure Costs and Potential in Ireland [Internet]. 2022 Feb [cited 2023 Apr 28]. Available from: https://www.seai.ie/publications/District-Heating-and-Cooling.pdf

50. Bauer F, Hulteberg C, Persson T, Tamm D. Biogas upgrading-Review of commercial technologies; Biogasuppgradering-Granskning av kommersiella tekniker. 2013 [cited 2022 Jun 15]; Available from: https://www.osti.gov/etdeweb/biblio/22090519

51. Gustafsson M, Cruz I, Svensson N, Karlsson M. Scenarios for upgrading and distribution of compressed and liquefied biogas — Energy, environmental, and economic analysis. J Clean Prod. 2020 May 20;256:120473.

52. O'connor S, Ehimen E, Pillai SC, Power N, Lyons GA, Bartlett J. An Investigation of the Potential Adoption of Anaerobic Digestion for Energy Production in Irish Farms. Environments 2021, Vol 8, Page 8 [Internet]. 2021 Jan 27 [cited 2022 Apr 21];8(2):8. Available from: https://www.mdpi.com/2076-3298/8/2/8/htm

53. Bacenetti J, Fusi A, Azapagic A. Environmental sustainability of integrating the organic Rankin cycle with anaerobic digestion and combined heat and power generation. Science of The Total Environment. 2019 Mar 25;658:684–96.

54. Scott A, Blanchard R. The Role of Anaerobic Digestion in Reducing Dairy Farm Greenhouse Gas Emissions. Sustainability 2021, Vol 13, Page 2612 [Internet]. 2021 Mar 1 [cited 2023 Apr 28];13(5):2612. Available from: https://www.mdpi.com/2071-1050/13/5/2612/htm

55. Burg V, Bowman G, Haubensak M, Baier U, Thees O. Valorization of an untapped resource: Energy and greenhouse gas emissions benefits of converting manure to biogas through anaerobic digestion. Resour Conserv Recycl. 2018 Sep 1;136:53–62.

56. Möller K. Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review. Agron Sustain Dev [Internet]. 2015 Jul 26 [cited 2023 Apr 28];35(3):1021–41. Available from: https://link.springer.com/article/10.1007/s13593-015-0284-3

57. Insam H, Gómez-Brandón M, Ascher J. Manure-based biogas fermentation residues – Friend or foe of soil fertility? Soil Biol Biochem. 2015 May 1;84:1–14.

58. Liebetrau J, Wellisch M, Lyng KA, Bochmann G, McCabe BK, Harris PW, et al. Potential and utilization of manure to generate biogas in seven countries [Internet]. 2021 [cited 2022 Apr 20]. Available from: https://www.ieabioenergy.com/wp-content/uploads/2021/07/Potential-utilization_WEB_END_NEW.pdf

59. Balcioglu G, Jeswani HK, Azapagic A. Evaluating the environmental and economic sustainability of energy from anaerobic digestion of different feedstocks in Turkey. Sustain Prod Consum. 2022 Jul 1;32:924–41.

60. IPCC. Climate change widespread, rapid, and intensifying [Internet]. 2021 [cited 2024 Apr 26]. Available from: https://www.ipcc.ch/2021/08/09/ar6-wg1-20210809-pr/

61. European Commission. 2050 long-term strategy [Internet]. 2016. Available from: https://ec.europa.eu/clima/policies/strategies/2050_en

62. European Commission. The European Green Deal [Internet]. 2019 [cited 2023 May 30]. Available from: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF

63. European Commision. Circular economy action plan [Internet]. 2023 [cited 2023 Jul 5]. Available from: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

64. European Commission. Farm to Fork Strategy [Internet]. 2020 [cited 2023 May 30]. Available from: https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en

65. Alberici S, Grimme W, Toop G. A Gas for Climate report Feasibility of REPowerEU 2030 targets, production potentials in the Member Biomethane production potentials in the EU [Internet]. 2022 [cited 2023 Feb 15]. Available from: https://gasforclimate2050.eu/

66. Lauer M. Methodology guideline on techno economic assessment (TEA). Generated in the framework of ThermalNet WP3B economics. Thermal Net TEA Methodology Guideline. 2008;

67. O'Shea R, Wall DM, Kilgallon I, Browne JD, Murphy JD. Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region. Appl Energy. 2017 Feb 15;188:237–56.

68. Murphy JD, McKeogh E. Technical, economic and environmental analysis of energy production from municipal solid waste. Renew Energy. 2004 Jun 1;29(7):1043–57.

69. Mahony T, O'flaherty V. Environmental Protection Agency. 2002 [cited 2022 Apr 26]. Feasibility Study for Centralized Anaerobic Digestion for Treatment of Various Wastes and Wastewaters in Sensitive Catchment Areas. Available from: https://eparesearch.epa.ie/safer/iso19115/displayISO19115.jsp?isoID=221

70. Singlitico A, Dussan K, Goggins J, O'shea R, Wall D, Murphy J, et al. Techno-economic Optimisation of Combined Anaerobic Digestion and Gasification of Food Waste as part of an Integrated Waste Management and Energy System . 25th European Biomass Conference and Exhibition [Internet]. 2017 [cited 2022 Apr 26]; Available from: https://www.researchgate.net/publication/317687717

71. Murphy JD, McCarthy K. Ethanol production from energy crops and wastes for use as a transport fuel in Ireland. Appl Energy. 2005 Oct 1;82(2):148–66.

72. Browne J, Nizami AS, Thamsiriroj T, Murphy JD. Assessing the cost of biofuel production with increasing penetration of the transport fuel market: A case study of gaseous biomethane in Ireland. Renewable and Sustainable Energy Reviews. 2011 Dec 1;15(9):4537–47.

73. Nolan T, Troy SM, Gilkinson S, Frost P, Xie S, Zhan X, et al. Economic analyses of pig manure treatment options in Ireland. Bioresour Technol. 2012 Feb 1;105:15–23.

74. Dennehy C, Lawlor PG, Gardiner GE, Jiang Y, Shalloo L, Zhan X. Stochastic modelling of the economic viability of on-farm co-digestion of pig manure and food waste in Ireland. Appl Energy. 2017 Nov 1;205:1528–37.

75. O'Connor S, Ehimen E, Pillai SC, Lyons G, Bartlett J. Economic and Environmental Analysis of Small-Scale Anaerobic Digestion Plants on Irish Dairy Farms. Energies 2020, Vol 13, Page 637 [Internet]. 2020 Feb 3 [cited 2022 May 23];13(3):637. Available from: https://www.mdpi.com/1996-1073/13/3/637/htm

76. Krey V, Masera O, Blanford USA G, Bruckner T, Cooke R, Fisher-Vanden K, et al. Annex II: Metrics & Methodology. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. 2014;

77. Murthy GS. Life-Cycle Assessment. In: Bioenergy : principles and applications. Wiley-Blackwell; 2016. p. 521–43.

78. European Commission. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) [Internet]. 2018 [cited 2022 Jul 21]. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC

79. O'Brien D, Shalloo L, Crosson P, Donnellan T, Farrelly N, Finnan J, et al. An evaluation of the effect of greenhouse gas accounting methods on a marginal abatement cost curve for Irish agricultural greenhouse gas emissions. Environ Sci Policy [Internet]. 2014;39:107–18. Available from: http://www.sciencedirect.com/science/article/pii/S1462901113001780

80. MacLeod M, Moran D, Eory V, Rees RM, Barnes A, Topp CFE, et al. Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. Agric Syst [Internet]. 2010;103(4):198–209. Available from: https://www.sciencedirect.com/science/article/pii/S0308521X1000003X

81. Ackrill R, Abdo H. On-farm anaerobic digestion uptake barriers and required incentives: A case study of the UK East Midlands region. J Clean Prod. 2020 Aug;264:121727.

82. Ricardo Energy & Environment. Assessment of Cost and Benefits of Biogas and Biomethane in Ireland [Internet]. 2017 [cited 2022 Aug 4]. Available from: https://www.seai.ie/publications/Assessment-of-Cost-and-Benefits-of-Biogas-and-Biomethane-in-Ireland.pdf

83. Pablo-Romero M del P, Sánchez-Braza A, Salvador-Ponce J, Sánchez-Labrador N. An overview of feed-in tariffs, premiums and tenders to promote electricity from biogas in the EU-28. Renewable and Sustainable Energy Reviews [Internet]. 2017;73:1366–79. Available from: https://www.sciencedirect.com/science/article/pii/S1364032117301429

84. SEAI. Support Scheme for Renewable Heat Scheme Overview [Internet]. 2019 [cited 2022 Aug 1]. Available from: https://www.seai.ie/publications/SSRH-Scheme-Details-.pdf

85. EIRGRID. Renewable Electricity Support Scheme 1 RESS 1 Final Auction Results [Internet]. 2020 [cited 2022 Jul 1]. Available from: https://www.eirgridgroup.com/site-files/library/EirGrid/207158-EirGrid-Renewable-Energy-Scheme-LR5.pdf

86. Bose A, O'Shea R, Lin R, Murphy JD. A perspective on novel cascading algal biomethane biorefinery systems. Bioresour Technol. 2020 May;304:123027.

87. Herbes C, Rilling B, Ringel M. Policy frameworks and voluntary markets for biomethane – How do different policies influence providers' product strategies? Energy Policy [Internet]. 2021;153:112292. Available from: https://www.sciencedirect.com/science/article/pii/S0301421521001610

88. Eyl-Mazzega MA, Mathieu C. Etudes de l'Ifri. 2019 [cited 2024 May 1]. Biogas and Biomethane in Europe: Lessons from Denmark, Germany and Italy. Available from: https://www.ifri.org/en/publications/etudes-de-lifri/biogas-and-biomethane-europe-lessons-denmark-germany-and-italy

89. Department of the Environment C and C. Ireland´s Draft National Biomethane Strategy [Internet]. 2024 [cited 2024 Apr 29]. Available from: https://www.gov.ie/en/consultation/9b170-consultation-on-the-draft-national-biomethane-strategy/

3 A perspective on methodologies and system boundaries to develop abatement cost for on-farm anaerobic digestion

A perspective on methodologies and system boundaries to develop abatement cost for on-farm anaerobic digestion.

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Abstract:

Marginal Abatement Cost Curves compare and assess greenhouse gas mitigation options available to various sectors of the economy. In the Irish agricultural sector, large anaerobic digestion facilities are currently considered a high-cost abatement solution. In prior studies of anaerobic digestion abatement costs, two options were assessed: the generation of heat and electricity from biogas (115 € tCO_{2eq}^{-1}) and the production of renewable heat from biomethane (280 € tCO_{2eq}^{-1}). Both scenarios encompass single cost values that may not capture the potential variable nature of such systems. In contrast, prior techno-economic analyses and lifecycle analyses can provide a comparison of the abatement costs of anaerobic digestion systems at a range of scales. This work compares two case studies (based on prior literature) for small and medium-scale on farm anaerobic digestion systems. The small-scale system is set in Ireland with cattle slurry collected in open tanks during the winter, while the medium scale system is set in the USA with cattle slurry collected periodically indoors all year-round. It was found that the abatement cost can vary between -117 to +79 € per t CO_{2eq}. The key variables that affected the abatement cost were additional revenue streams such as biofertiliser sales, displaced energy savings, and additional incentives and emissions savings within the system boundary. Including only some of these options in the analysis resulted in higher abatement costs being reported. Based on the variation between system topologies and therefore system boundaries, assigning a single mitigation cost to anaerobic digestion systems may not be representative.

Keywords: Anaerobic Digestion, Techno-Economic Assessment, Abatement Cost, GHG mitigation, Life-Cycle Analysis.

3.1 Introduction

With the increasing threat of global warming due to rising greenhouse gas (GHG) emissions, climate mitigation has become a leading priority for the European Union (EU). Through the European Parliament's environmental policies, a goal has been set to reduce GHG emissions in all sectors of the economy and to achieve carbon neutrality by 2050 (1). In 2019, the EU emitted a total of 4,057 Mt of carbon dioxide equivalent (CO_{2eq}), of which the agriculture sector was responsible for 11% (2). In agriculture, there are limited mitigation options that can reduce GHG emissions and improve manure and livestock management while reducing waste production (3). Mitigation options can be limited to reducing the demand of consumers for meat and dairy products or converting arable land to permanent pasture or wood land to sequester carbon in the soil (4). Technologies such as anaerobic digestion (AD) can provide a manure management option that mitigates GHG emissions by converting manures and slurries into biogas that can replace fossil fuels, as well as reducing fugitive methane emissions from manure storage (5). On-farm AD may be a suitable mitigation option in Ireland owing to the wide availability of agricultural biomass. With over 90% of agricultural land covered by grass, excess grass, which is not used as livestock fodder, could provide a potential feedstock to produce biogas in Ireland (6). Furthermore, the livestock sector produces a significant share of agricultural waste in the form of manure (or slurry) produced by ca. 7 million cattle (7) in a country with a population of ca. 5 million people. Previous studies have found that grass silage should be co-digested with slurry to ensure sufficient nutrients are available to enable the effective production of biogas (8).

On-farm AD can facilitate the progression to a sustainable agricultural sector by processing agricultural waste (such as slurry) on-site, reducing the overall emissions from manure management, and providing an indigenous renewable energy source in the form of biogas. AD simultaneously provides energy and fuel generation whilst reducing water, soil, and air pollution (9). There are drawbacks associated with anaerobic digestion such as fugitive methane emissions (ranging from 2% to 10%) from different sources within the process (including biogas production, upgrading to biomethane, and digestate storage) (10). These can be minimised through careful design and prudent operation practices (such as the implementation of covered digestate storage) (11). The biofertiliser (digestate) produced as a by-product of AD can displace raw manure (slurry) use on farms and reduce the associated risk of water contamination and GHG emissions. Digestate use also mitigates odours associated with manure storage and decomposition whilst removing pathogens (12). Pyrolysis of digestate may also be implemented to produce biochar that can be used as an additive to improve the digestion process and boost the overall biogas production, or it can be spread on the land as a soil amendment facilitating carbon sequestration and net zero carbon emissions within the process (13).

A marginal abatement cost curve (MACC) can be a useful tool to evaluate the cost and abatement potential of various mitigation technologies. This curve orders the options based on the cost of GHG abatement of a measure and by the quantity of GHG emissions mitigated (17). Abatement measures are ranked based on the cost-effectiveness the technology provides in a specific sector, and the results of these rankings have been used by many governments to establish low carbon policies (18). In Ireland's Climate Action Plan 2019 (19), a MACC was used to assess the impact of technology adoption across all sectors of the economy to reach the decarbonisation target of 30% GHG emissions reduction by 2030. Furthermore, a specific MACC for the agriculture sector was developed to compare different energy mitigation measures (Table 3-1) (20). Some of the measures considered for GHG mitigation included: the reduction of energy consumption on dairy farms (Farm Energy); the increase of biomass use from sources such as wood thinnings and sawmill (Forestry); the use of willow and miscanthus to produce heat (Biomass-Heat); the use of willow chips and peat to generate electricity (Biomass-Electricity); production of biodiesel from oil seed rape to substitute fossils fuels imports (biodiesel); and production of bioethanol from sugar beet to substitute fossils fuel imports (bioethanol).

Table 3-1 MACC results for the agriculture sector of Ireland for 2021-2030. Adapted from (20).

Scenario	Scenario description	Marginal Abatement Cost (€ / t CO_{2eq})	Abatement Potential (kt CO_{2eq})
Farm Energy	Increased Farm Energy Efficiency through energy consumption reduction on-site.	-359	29
Forestry (Wood / Wood Residue)	Use of fuel-wood, sawmill residues and waste wood for energy generation.	-30.7	759
Biomass (Heat)	Increased use of short rotation coppice and miscanthus biomass for heat production.	-20	179
Biomass (Electricity)	Combustion of willow and miscanthus in biomass boilers for energy generation.	-10	196
Biodiesel	Biodiesel production from Oilseed Rape.	90	174
Biogas AD	Biogas production from co-digestion of slurry and grass silage for energy generation.	115	224
Bioethanol	Bioethanol production from Sugar Beet.	200	51
Biomethane	Biomethane production from biogas upgrading for grid injection.	280	150

As part of the analysis, two anaerobic digestion options were considered as potential mitigation options within the agriculture and forestry sectors as shown in Table 3-1. The first option was related to the production of biogas via the digestion of slurry and grass silage to generate heat and electricity (115 €/tCO_{2eq}). The second option was to produce biomethane from biogas, followed by the use of this biomethane to produce renewable heat (280 €/tCO_{2eq}). Both options were seen as high-cost abatement solutions for the Irish agricultural sector based on a price point of 50 €/tCO_{2eq} (20). MACC analyses are dependent on the methodology used and the inputs considered for the calculations. As such, the MACC may not capture the entire cost-effectiveness of the technology depending on the methodology used to calculate the mitigation potential (17). Furthermore, MACC analyses have largely been completed for large-scale operations that encompass whole energy sectors, where little granularity of the technologies or options available are provided (21,22). As a result, mitigation options such as anaerobic digestion have been represented by a single value related to a single scenario that may not encompass or describe the impact of different variables which can change between different systems (based on scale, type, or energy output). Anaerobic digestion systems vary in scale, design, technology, feedstock, and function, and these variabilities cannot be covered by a single scenario within a MACC.

This study aims to provide a perspective on previous methodologies used for assessing the economic and environmental feasibility of on-farm anaerobic digestion systems. To the best of the authors' knowledge no prior literature has outlined the importance of the assumptions made in the calculation of the abatement potential and associated cost for on-farm anaerobic digestion systems. Thus, this work will advance beyond the state of the art by encompassing a more holistic methodology for the calculation of the abatement cost of a technology such as anaerobic digestion. To represent all the potential costs and benefits that a technology may provide, based on its abatement cost and potential, clarity on the variables and assumptions selected for the construction of the abatement curve is required. For this work, methodologies used for calculating the cost and abatement potential of on-farm anaerobic digestion systems will be reviewed. The abatement cost of on-farm anaerobic digestion will be assessed for two case studies at different scales. Results will be compared against the values provided for anaerobic digestion in the Climate Action Plan shown in Table 3-1. Furthermore, the main variables and assumptions required to calculate the mitigation potential of on-farm anaerobic digestion and their impact on results will be explored.

3.2 Methodology

3.2.1 Areas of focus within the system boundary of an on-farm AD system

The AD process at a farm-scale can be divided into three main areas of focus for an economic analysis: 1) feedstock production/acquisition and transport including the operations and costs associated with the collection and transportation of feedstock to the AD plant; 2) pre-treatment and AD processes including the capital and operational costs of processing the feedstock and conversion to biogas and digestate, and 3) biogas post-processing/utilisation and coproduct handling including but not limited to the cost of upgrading the biogas and the handling of the digestate produced from the AD process (23). The processes associated with each area of focus may vary depending on the design of an individual system. Table 3-2 highlights previous literature from a select set of works of TEA and LCA analyses which includes a description of the aforementioned areas of focus. These studies were used as they all included at least one process relating to the three areas of focus of the AD process outlined above. A full list of the articles reviewed can be found in detail in Appendix A.1. Providing a system boundary facilitates the development of a process model and calculation of the mitigation potential, cost, and revenue associated with each area.

Table 3-2 Areas of Focus in previous literature studies including TEA and LCA analyses of on-farm AD systems.

Areas of Focus	**Associated Processes**	**TEA**						**TEA + LCA**			**LCA**		
Feedstock production / Acquisition and Transport	Feedstock Acquisition	X	X	X	X	X	X	X	X	X	X		
	Feedstock Handling	X	X	X			X	X	X	X	X		X
	Manure and/or Feedstock Storage							X	X	X	X	X	X
	Transportation by Land or Pipe	X						X	X	X	X		X
	Farm Labour		X					X		X			
Pre-treatment and Anaerobic Digestion	Construction of Anaerobic Digester	X	X	X	X	X	X	X	X	X	X	X	X
	Purchase of CHP unit	X	X	X	X	X	X	X	X	X	X	X	X
	Acquisition of Heat Exchange and Water Pumps	X	X	X	X		X		X				
	Maintenance and Repair of the System	X	X	X	X		X	X	X	X			
	Insurance			X	X			X	X	X			
	Plant Labour		X	X	X		X	X	X	X			
Biogas Post Processing / Utilisation and coproduct handling	Connection to Gas Grid or Electricity Grid					X							X
	Purchase of Gas Purification Unit					X							X
	Operation of Upgrading System					X							X
	Sale of Electricity and/or Heat Generated	X	X	X	X	X	X	X	X	X	X	X	X
	Sale of Biomethane Produced					X							
	Land Spreading of Digestate	X		X	X	X	X	X			X	X	
	Treatment of Digestate						X			X		X	
	Sale of Digestate as Biofertiliser		X				X	X	X		X	X	
Source		(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)

Note: X marks studies that contain the variables or process detailed in the leftmost column of the table.

For the TEA and LCA, the selection of the processes within the system boundary determines the scope of the analysis and can affect the estimates of operating cost, capital cost, revenues, and the total carbon abatement of the overall process. Furthermore, process models need to be created around this methodology to include all the relevant variables based on the farm and AD system for which the analysis is being undertaken. A representative farm model, which captures the entire farm context of the region of analysis, is preferred to account for all inputs and outputs considered for the TEA and LCA. This can be quite extensive based on the data and resources required to determine the multitude of interacting factors that might impact upon the viability of an AD system in a real-world context. However, once the estimations are set, the constructed model can be easily adapted to a variety of farm types and scales (36). For that reason, a methodology in which the processes considered for the analysis are clear, such as the one shown in Figure 3-1, for the region of analysis facilitates the use of a single modelling tool that can replicate different scenarios and compare the mitigation potential taking into consideration variations in the calculation of the abatement cost.

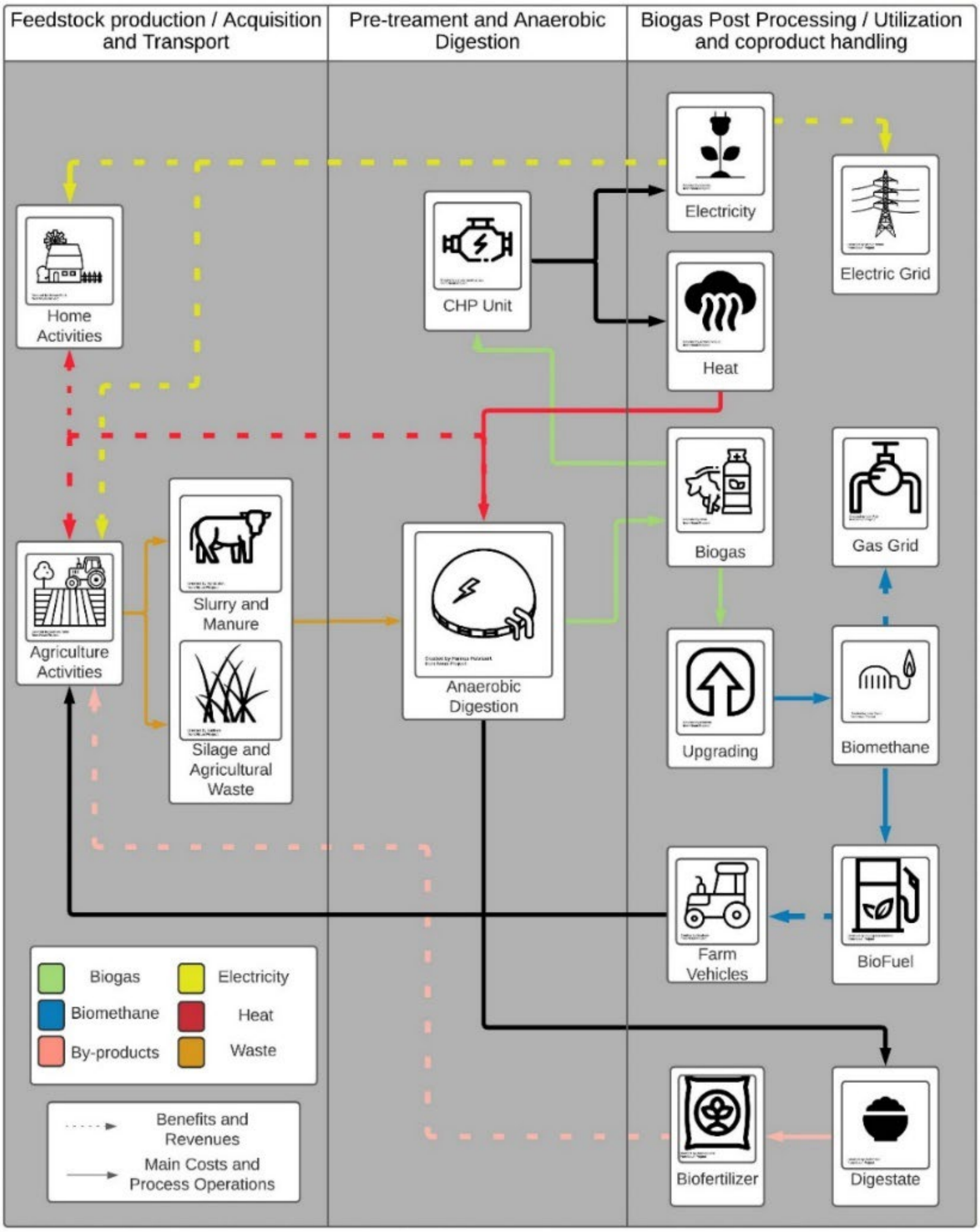

Figure 3-1 Example of an on-farm AD system, including the costs and revenues taken with an economic diversification approach. Elements of the graphics sourced from The Noun Project (37).

3.2.2 Capital and operational costs of on-farm AD

In a TEA, the costs can be divided into the cost of capital expenditure (CapEx) and operational expenditure (OpEx). For on-farm AD, the main capital expenditure can be designated to the investment required for the plant design which in turn is defined by the type of feedstock used, the digester size desired, and the available technology (38). Once the type of plant has been selected, the total construction budget is divided into costs such as the engineering and permits required for its construction, construction insurance, interconnection costs, developer's fee, equipment acquisition/installation costs, and land acquisition (39). Furthermore, depending on the business model there may be additional capital expenses including for a CHP unit, digestate treatment systems, and an upgrading unit to convert the biogas to biomethane (40). CapEx cost can also vary depending on the region where the technology is applied as some of the equipment may need to be imported from another country, incurring additional costs in the form of taxes.

For OpEx, the associated costs are the operation and maintenance of the AD plant. These costs can include the daily operational labour, acquisition of feedstock, chemical and consumables required for the system, insurance, taxes, and maintenance of the mechanical systems (39). Depending on the type of feedstock, the cost associated with the operation can increase if there is a need for additional processes such as waste screening, removal of contaminants, and the need for loading and unloading of feedstock based on the size and type of digester (38). Furthermore, if the system is not correctly maintained, over time there may be a need to replace some of the mechanical and electrical elements of the system. It is also important to take into consideration an operation and maintenance (O&M) reserve fund to cover unexpected costs in the project such as the need to replace any equipment due to malfunctions (39). Finally, the cost of the parasitic electrical and thermal energy demand based on the selected AD technology must also be considered. For a process model to have an accurate estimation of the CapEx and OpEx, it is important to consider all associated processes to the technology that will be considered as part of the economic evaluation of the AD system as opposed to part of the farm function. For most of the TEAs and LCAs reviewed in the literature, these costs are considered within the areas of focus of the AD process as shown in Table 3-3.

Table 3-3 Capital and operational costs for on-farm AD systems reported in previous literature considering TEA and LCA analysis.

Costs		**TEA**							**TEA + LCA**			
Capital	Plant Construction	X	X	X	X				X		X	
	Construction Insurance or Contingency								X			
	Grid Connection Cost					X						
	Equipment Acquisition/Installation cost	X	X	X	X	X	X	X	X	X	X	X
	Land Acquisition and/or Civil Works		X	X	X		X	X	X		X	X
	Upgrading Unit	X				X						
Operational	Operational Labour	X	X				X		X	X	X	X
	Acquisition of Feedstock		X	X			X	X			X	X
	Chemicals and Consumables for the System					X	X		X		X	
	Insurance for the System			X	X					X	X	
	Internal Energy Consumption		X	X	X	X	X		X	X	X	X
	Maintenance	X	X	X	X		X	X	X	X	X	X
	Handling of Feedstock	X					X	X			X	X
	Digestate Treatment		X				X				X	
Source		(24)	(25)	(26)	(27)	(28)	(29)	(41)	(42)	(30)	(31)	(32)

Note: X marks that the study contains the variables or process detailed in the left side of the table.

3.2.3 Economic diversification and revenues from on-farm AD

The main revenues obtained from on-farm AD are dependent on the post-processing and utilisation of biogas. A CHP unit fuelled by biogas can generate renewable electricity and heat that can be sold to generate revenues. In the case of electricity, these revenues come from Feed-in-Tariffs (FiT) set by regulators within countries or regions that are contract-based with a maximum duration of 15-20 years. Different electricity prices are based on the sources of biomass or the capacity of the plant as shown in Table 3-4. In the case of heat, revenues can be generated through renewable heat incentives (RHI), such as those used in the UK and Ireland that are tier-based depending on the AD plant size, and similar to FIT tariffs are available for 15-20 years. A caveat in reading Table 3-4 is the ever-changing systems for reimbursement in different countries over time. The values presented illustrate typical ways of remunerating renewable energy at a moment in time for selected countries. However, it can be noted that the incentive typically increases when the system scale is small, thus encouraging the adoption of small-scale on-farm AD systems. Such granularity of incentives is considered crucial by numerous governments to enable a profitable and competitive market for biogas plants (43), whilst encouraging premium returns to the sector at a local level which cannot avail of large (industrial) economies of scale. However, if additional products and benefits are provided by an on-farm AD system over time and are integrated into the farm supply chain, the process can increase the potential for financial sustainability without the need for subsidies.

Table 3-4 Financial benefits and support payments for AD in selected countries. Adapted from Pablo-Romero et al. (44), RES Legal (45) and RHI from the UK and Ireland (46,47).

Country	Contract Duration*	Determining factors of the prices	Revenue from Biogas	Source
Germany	20 years	Plant size and origin of fuel (biogas from bio-waste, manure, landfill, sewage gas)	**Biomass from bio-waste:** €ct 13.05–14.88 per kWh **Biogas from manure:** €ct 23.13 per kWh	(45)
United Kingdom	20 years	Installed capacity of the plant.	**Plant Capacity:** **≤250 kWe:** €ct 8.83 per kWh **>250 kWe and ≤500 kWe:** €ct 8.15 per kWh **>500 kWe:** €ct 8.4 per kWh **Anaerobic Digestion Heating Systems:** **Capacity** <200 MWth: 4.83 GBP (in pence) **Capacity** ≥200 kWth - <600 kWth: 3.79 GBP (in pence) **Capacity** ≥600 kWth: 1.21 GBP (in pence)	(44,47)
France	15 years	The capacity of the plant and the energy performance	**Plant Capacity:** **≤150 kWe:** €ct 9.745 per kWh **≥2 MWe:** €ct 8.121 per kWh A bonus of €ct 4 is granted to the plant if at least 60% or higher amount of the biomass contains livestock manure.	(44)
Ireland	15 years	Technology dependent (landfill gas, anaerobic digestion) and size of the CHP or non-CHP plant	**Anaerobic digestion CHP plant capacity (No longer open for applications):** **CHP≤500 kWe:** €ct 15.7 per kWh **CHP>500 kWe:** €ct 13.66 per kWh **Non-CHP≤500 kWe:** €ct 11.55 per kWh **Non-CHP>500 kWe:** €ct 10.5 per kWh **Anaerobic Digestion Heating Systems:** **Tier 1** (0-300 MWh/yr): 2.95 €ct /kWh **Tier 2** (300-1,000 MWh/yr): 2.95 €ct /kWh **Tier 3** (1,000-2,400 MWh/yr): 0.50 €ct /kWh	(44,46)

*Period guaranteed by each government to offer fixed prices per kWh generated.

Based on the processes considered in the business model selected for the on-farm AD system, the sources of revenues may vary between different TEAs, as shown in Table 3-5. The main source of income for most on-farm AD systems is the sale of electricity generated by the CHP unit. However, depending on the region of analysis, an economic diversification approach may be applied. This approach considers the generation of multiple products, which can provide benefits in terms of cost reduction to the process and additional income streams (48). This concept for on-farm AD is extended to other potential outputs within the boundary of the on-farm AD process that are non-energy related.

The inclusion of the digestate (biofertiliser) and volatile fatty acids could diversify the product portfolio of the AD industry to increase its viability and feasibility. For example, carbohydrates present in the liquid effluent may be used to produce carboxylic acids by using membrane filtration which can be sold as platform chemicals (49). Digestate can be converted to bio-oil and bio-char with the integration of pyrolysis. Through the use of novel upgrading technologies, biogas can be converted into methanol, bio-CNG, and/or liquid drop-in fuels (50). Biomethane can also be used as a vehicle fuel with the use of compressed natural gas (CNG) service stations (51). With the increase in support schemes and technical advancements, there has been an increase in natural gas vehicles (NVGs) in the EU; ca. 1.3 million vehicles were reported in operation in 2015. Up to 3,345 CNG filling stations, of which 697 were biomethane filling stations, have been reported in selected EU countries (Germany, Italy, Austria, Finland, Sweden, Iceland, and Norway) (12). Biomethane can also be a substitute for natural gas if it is injected into the gas grid for use by traditional end-users (power plants, industries, and households). However, for this to be possible, the biomethane needs to comply with the gas purity requirements of the relevant gas grid.

The sources of income or revenues may vary between different TEAs, this is dependent on the business model selected and the processes considered for the analysis, as shown in Table 3-5. Furthermore, if the uncertainty of external variables which can vary between regions is added, affecting both the cost and revenues that can change with time, the results can vary between each study. To account for this variability, some TEAs include additional sensitivity analysis to assess which variables are more sensitive to external variables within the study scope.

Table 3-5 Main revenues generated from on-farm AD systems reported in previous literature considering TEA and LCA analysis.

Revenues	**TEA**						**TEA + LCA**		
Sale of electricity to the grid	X	X	X	X	X	X	X	X	X
Sale of biogas and/or biomethane	X				X	X			
Sale of heat in the district heating network							X		X
Sales of by-products from digestate or co-products from the system	X							X	X
Sales of biofertiliser (digestate)	X	X				X			
Offset of current heat and/or electricity costs avoided from current farm demand*.		X	X	X			X		X
Source	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)

Note: X marks that the study contains the variables or process detailed in the left side of the table.
*This stream is considered a revenue as it reduces the cost of farm processes not related to the AD process.

3.2.4 Sensitivity analysis and the variability in costs and revenues

Sensitivity analyses are used to evaluate the uncertainty that independent variables may pose to dependent variables in a mathematical model based on a series of assumptions. This allows for the identification of the input factors that contribute to the uncertainty of the model for later optimisation (52). For investment projects, it is essential to add a sensitivity analysis as an evaluation procedure to assess the feasibility of the project. This includes input values (such as the income, costs, value of investments), and how external factors may affect the total investment project evaluation (53). To assess the impact of external factors within the study scope on the profitability of on-farm AD, it is necessary to assess changes in the inputs and outputs of the systems that directly affect CapEx and OpEx during the lifetime of the project. Such external factors include government energy policies in the region and the technological development of AD at the time of the analysis, which directly affects the economic performance of the plant (54).

In a TEA, sensitivity analysis can be conducted to assess the impact of the OpEx and the revenues on the key parameters such as the payback period, profitability index, and the net present value (55). However, depending on the type of analysis, the investment capital related to the CapEx may be included in the sensitivity analysis if different technologies or systems are evaluated in the process (29). Some examples of the OpEx considered include operating capacity, power efficiency, electricity price, gas price, feedstock price (manure, silage, or other agricultural feedstock), farm size, pre-treatment costs, and discount rate as shown in Table 3-6. For the revenues, these variables may include applied subsidies, electricity, and heat buyback price, solid digestate price, liquid effluent price, biomethane price, liquid, and solid fertiliser price (Table 3-6). Once the variables are identified, they are altered by a set variation value to identify the variables that have the greatest impact on the output(s) and the results can be visualised using a tornado plot. This allows for the identification of the external agents that are most relevant for uncertainty analysis using a Monte Carlo simulation which is conducted by repeatedly running the model with different values of the sensitive parameters sampled from a given probability distribution (52).

Table 3-6 Variables evaluated for sensitivity analysis in recent TEA literature studies.

Variables analysed in Sensitivity Analysis	**TEA**				**TEA + LCA**
Operating Capacity			X		X
Feedstock Price	X	X		X	X
Farm Size		X	X		
Capital Cost	X		X	X	X
Pre-treatment Costs		X			
Discount Rate		X	X		
Applied Subsidies				X	
Electricity and Heat Buyback Price		X	X	X	
Digestate and Effluent Price					X
Fertiliser Price				X	
Source	(24)	(26)	(27)	(29)	(31)

Note: X marks that the study contains the variables or process detailed in the left side of the table.

3.2.5 Implementation of TEA and LCA for on-farm AD

An indication of the financial feasibility of on-farm AD can be estimated from the results of recent TEA scenarios undertaken in different regions across the globe. These results tie together the processing capacity of the plant selected for the analysis based on the CapEx, OpEx, and the break-even prices of the products considered within the AD process in the region of analysis. The most prominent key indicators included in the results of recent TEA analyses include the IRR (Internal Rate of Return), NPV (Net Present Value), and the payback period as shown in Table 3-7. The IRR plays a crucial role in assessing the viability and financial feasibility of the project before investing. The NPV provides the present value of all future cash flow the project will generate during the lifetime of the project, which in most of the TEAs reviewed for on-farm AD is in the range of 15-30 years. Each TEA selects a particular discount rate based on the assumptions of the inflation in the region of analysis, the weighted average cost of capital of the investor, and investor attitudes toward risk; typically, this rate is in the range of 5% to 10%, although it is commonly recommended to select a discount rate of 10% for renewable energy investments if there is no previous data for the region (56). Furthermore, most of the TEAs reviewed provide a simple payback period, in comparison to a discounted payback period, which provides a more realistic representation of the payback period by taking into consideration the value of money over time.

Table 3-7 Key Indicators reported by recent TEA analysis in the literature for on-farm AD.

TEA Key Indicators	**Khan et al. (2014) (24)**	**Wresta et al. (2015) (25)**	**Imeni et al. (2019) (26)**	**Imeni et al. (2019) (27)**	**Perta et al. (2019) (28)**	**Villarroel-Schneider et al. (2020) (29)**	**O'Connor et al. (2020) (30)**	**Aui et al. (2019) (31)**
IRR	X	X	X	X	X		X	X
NPV	X	X	X	X	X	X	X	X
LCOE	X					X		
Simple Payback Period	X	X	X	X	X	X	X	X
Discounted Payback Period						X	X	

Note: X marks that the study contains the variables or process detailed in the left side of the table.

In terms of LCAs, most studies follow the International Organization for Standardizations (ISO) 14040 and 14044 standards (31) although, for Europe, the International Reference Life Cycle Data System (ILCD) handbook guide provides a detailed description on how to carry out the analysis following the definitions established by the European guidelines (32). This includes the emissions analysis that needs to be set based on the REDII methodology to assess GHG emissions from the production and use of biomass-derived fuels; for the co-digestion of crop biomass this would include everything from the cultivation of the crop right through to biogas upgrading and/or injection for its use as a transport fuel as shown in Equation 3.1. If the fuel is used for heat and/or electricity production, an energy conversion factor needs to be included to account for the efficiency of the heat or electricity generation process when comparing the energy produced to the respective fossil fuel comparator.

Equation 3-1 Emissions analysed using REDII methodology for GHG assessment.

$$E = \sum_{1}^{n} S_n \times \left(e_{ec,n} + e_{td,feedstock,n} + e_{l,n} - e_{sca,n}\right) + e_p + e_{td,product} + e_u - e_{ccs} - e_{ccr}$$

Where E amounts to the total emissions produced in the biogas as primary energy (before energy conversion to electricity, heat, or transport fuel); S_n is the energy share provided by feedstock n for the production of the biofuel, $e_{ec,n}$ is the emissions associated with the extraction and cultivation of feedstock n; $e_{td,feedstock,n}$is the emissions from the transport of feedstock n to the digester; e_l is the emissions from carbon stock changes caused by land-use change; e_p is the emissions from processing; e_{td} is the emissions from transport and distribution of the products; and e_u is the emissions from fuel in use, emitted during combustion, which shall be assumed as 0 for biofuels and bioliquids . The emissions savings are accounted for by e_{sca} from improved agricultural management of feedstock, e_{ccs} and e_{ccr} from CO_2 capture from geological storage and fuel replacement (57).

In the case of co-product allocation in which one or more useful products are produced in the production system (such as heat, transport fuel, biofertiliser, etc.) it is necessary to select an allocation method so that the emissions can be divided between the co-products (35). To achieve this, some authors recommend expanding the system boundary of the LCA to include the life-cycle of co- or by-products to correctly represent the environmental performance of the biofuel system (58). Furthermore, the LCA boundary determines the mitigation potential of the on-farm AD system based on the GHG abatement mitigation measures considered in the boundary as shown in Table 3-8.

Table 3-8 The main GHG mitigation measures taken into consideration for literature LCAs for on-farm AD.

GHG Mitigation Potential	O'Connor et al. (2020) (30)	Aui et al. (2019) (31)	Croxatto Vega et al. (2020) (32)	Nayal et al. (2016) (33)	Pardo et al. (2017) (34)	Adams et al. (2019) (35)
Manure Management	X		X	X	X	X
Displacement of Farm Energy Demand	X	X	X	X		
Displacement of Energy Exported	X			X	X	X
Displacement of Mineral and Organic Fertilisers		X		X	X	

Note: X marks that the study contains the variables or process detailed in the left side of the table.

3.2.6 Abatement cost curve methodology

With the values obtained from both the TEA and LCA, it is possible to calculate the abatement cost that can assess the impact of technology adoption compared to other technologies in the agricultural sector based on the abatement cost and the magnitude of abatement possible. The abatement cost can be calculated using the IPCC methodology (15) as shown in Equation 3.2

Equation 3-2 Abatement cost calculation.

$$\boldsymbol{Abatement\ cost}\left(\frac{€}{tCO_{2eq}}\right) = \frac{\boldsymbol{-NPV}}{\boldsymbol{DLA}}$$

Where the NPV is obtained from the result of the TEA and the discounted lifetime abatement (DLA) is calculated from the sum of the discounted annual abatement (DA) as shown in Equation 3.3.

Equation 3-3 Discounted annual emissions calculation.

$$DLA\ (tCO_{2eq}) = \sum_{t=0}^{n} \boldsymbol{DA_t} = \sum_{t=0}^{n} \frac{\boldsymbol{Net\ GHG\ Abatement}}{\boldsymbol{(1+r)^t}}$$

Where the net GHG abatement ($tCO_{2eq}\ a^{-1}$) is obtained from the result of the LCA, r is the discount rate, t is the year of analysis, and n is the number of years based on the lifetime of the project.

An abatement cost analysis evaluates the potential for GHG mitigation based on two main variables: the cost of implementing the measure and the effectiveness in reducing the emissions in the sector. Based on Sathaye and Meyers (59), MACCs follow three typical approaches.

The partial approach evaluates a measure against a reference technology in which the incremental changes in emissions and costs are calculated and ranked based on the cost-effectiveness of the measure. The results are ranked independently without taking into consideration the possible interdependence among the options making this approach the shortest and simplest; however, this can sometimes cause misinterpretation of the results.

The retrospective approach is similar to the partial approach in the initial steps, but multiple calculations are required to evaluate each option or measure based on the interdependence of the variables present and the interaction these have with all of the previously implemented options. Compared to the partial approach, it is slower as it requires more calculations and does not consider the interaction between more expensive options on previously selected options.

The integrated system approach requires a well-defined baseline and the use of an optimisation model that reacts automatically to marginal changes in the demand and supply side every time the model is run. This approach is the most complete option as it considers all possible interdependencies within the system boundary of the analysis.

MACC analyses for the agriculture sector have been developed for several countries where AD is proposed as a mitigation measure to reduce GHG emissions. For the majority of MACCs that include AD as a mitigation technology, the preferred methodology is the partial approach (20,60,61), despite being more prone to misinterpretations due to the lack of data availability used for its construction. A recent MACC (62) used a retrospective approach to evaluate the interdependence of the variables within the analysis. The abatement cost and potential can be quite dependent on the region of analysis, the size of the farm, the type of feedstock, and the possibility to commercialise the co-benefits. Thus, the selection of all the possible variables affecting the system under analysis is essential in terms of considering all measures that contribute to the mitigation potential of the on-farm AD system.

3.2.7 Considerations for the analysis of abatement cost for on-farm AD

For the majority of TEAs and LCAs reviewed, the processes and variables selected were dependent on the region of analysis which influenced the main considerations and assumptions selected for the on-farm AD system. As shown in Table 3-2 the main processes included in all of the analyses are the feedstock acquisition, the construction of the anaerobic digester, purchase of CHP unit, and the sale of electricity and/or heat generated. These processes are the baseline assumptions considered in the reviewed TEAs and LCAs as part of the profitability and mitigation potential of on-farm AD. This boundary in most cases can be limited as it only takes into consideration the main process of AD, namely the production of biogas to generate power without considering the co-products and by-products produced by the process and the environmental benefits of the technology. To characterise the effect of the different variables considered within the boundary of the study for on-farm AD systems, two studies (presented in Table 3-9) that included both TEA and LCA results with a clear methodology were selected to calculate the abatement cost for small and medium-scale systems. Both studies provided the assumptions considered for the selection of the variables for the TEA and LCA and explained in detail how each scenario was selected for the analysis of the study.

Scenarios S1 to S4 are based in Ireland, and scenarios S5 to S7 are based in the USA. While the feedstock differs in both the Irish and US scenarios, both studies represent on-farm AD systems. Typically, in Ireland slurry is collected in open tanks in the winter period for 16 weeks when cattle are housed indoors, the cattle are kept outdoors on pasture during the rest of the year (63). In the USA, the cattle are housed year-round in feedlot operations in which manure is collected periodically based on the amount accumulated and the weather conditions (64). In the Irish scenarios (S1 – S4), the annual slurry collected is 10.1 t cow^{-1} a^{-1} with a total solid content of 8.75% resulting in 0.88 tDM cow^{-1} a^{-1} (30). In the USA scenarios (S5 – S7), the annual manure collected is 12.8 t cow^{-1} a^{-1} with a total solid content of 12% resulting in 1.53 tDM cow^{-1} a^{-1} (31). There are obvious differences in the size of the systems assessed; the Irish system can be described as small-scale with an electrical output of <100kW_e whilst the US process is of medium-scale (>100 kW_e) (30).

Table 3-9 Case study scenarios for on-farm AD systems in Ireland (small-scale) and the USA (medium scale) for the calculation of the abatement cost and potential of anaerobic digestion.

Scenario	Manure Source	Herd Size	Feedstock (tonnes fresh weight a^{-1})	Digester Size (m^3)	CHP (kW_e)	Location	Source
S1	Dairy Cows	100	1,070 (Grass Silage) 1,010 (Slurry)	NA	26	Ireland	(30)
S2	Dairy Cows	150	1,199 (Grass Silage) 1,515 (Slurry)	NA	39		
S3	Dairy Cows	200	1,328 (Grass Silage) 2,020 (Slurry)	NA	46		
S4	Dairy Cows	250	1,457 (Grass Silage) 2,525 (Slurry)	NA	55		
S5	Beef Cattle	2,392	3,313 (Corn Husk) 30,558 (Slurry)	3,670	500	US	(31)
S6	Beef Cattle	3,564	3,313 (Rye) 45,515 (Slurry)	3,670	500		
S7	Beef Cattle	3,458	3,313 (Wheat) 44,165 (Slurry)	3,670	500		

3.2.8 TEA assumptions

For the calculation of the TEA for scenarios S1 to S7, each of the studies considered different variables for the CapEx, OpEx, and revenues generated by the project to calculate the NPV based on the region of analysis. For both studies, CapEx considered the cost of the equipment installation at the AD plant and the cost associated with the CHP electrical plant. The Irish scenarios (S1 – S4) estimated this cost on the average establishment cost based on the installed electrical capacity (kWe) of the on-farm AD systems based on reports from Europe (30). The USA scenarios (S5 – S7) also included in the CapEx the cost for storage of slurry and liquid by-products in the form of a sludge holding tank for the slurry based on the total head of cattle and a lagoon for the average liquid effluent produced per head of cattle (31). The OpEX for both studies accounted for the maintenance, labour, and insurance for the operation of the plant; however, the Irish scenarios (S1 – S4) omitted taxes and interest from the calculation as the authors stated that this would give a distorted representation of the cost of financing (30). The USA scenarios (S5 – S7) also included the cost of raw materials such as the feedstock acquisition cost

(Rye, Wheat, and Corn Stover) and raw manure obtained from cattle feedlot operations, and the waste handling cost for the solid digestate (31).

For revenues, both studies considered incentives as part of the income. The Irish scenarios (S1 – S4) considered two different incentives for energy, the renewable energy FiT scheme for the electricity exported to the grid at a rate of 15.8 c€ kWh^{-1} for CHP with capacity ≤ 500kW and the RHI scheme based on the heat produced at a rate of 2.95 c€ kWh^{-1} for AD plants generating less than 300 MWh a^{-1} (30). For the US scenarios (S5 – S7), the incentives came from the Renewable Electricity Production Tax Credit based on the electricity generated by the system using a cost of $0.015 USD $kWhe^{-1}$. Additionally, this tax credit provides an incentive through a by-product credit claim that provide $35.25 USD per metric ton for solid effluent and $2.64 USD per metric ton for liquid effluent if these are reused as fertilisers on the farm (31). In addition to the incentives, the Irish scenarios (S1 – S4) consider additional revenues from the sale of exported heat via a district heating system at a rate of 3 c€ kWh^{-} taking into consideration the cost of infrastructure and from the cost-saving from avoided electricity and heat use on the farm. The electricity saving is based on the purchase price of 19.9 c€ kWh^{-1} from the electric grid for consumption less than 0.02 GWh/yr and 15.1 c€ kWh^{-1} for consumption between 0.02 and 0.5 GWh a^{-1}. Meanwhile, thermal energy savings were based on the cost of displacing kerosene as a fuel for heating at a cost of 7.8 c€ kWh^{-1} (based on an energy input of 36.4 MJ L^{-1} and a price of 80 c€ L^{-1}) (30).

3.2.9 LCA assumptions

For the calculations of the net GHG abatement, each of the studies took different approaches based on the processes considered in each LCA methodology. For both the Irish and US scenarios, the overall Net GHG abatements (kg CO2eq / yr) were calculated by subtracting the total GHG emissions produced by the process minus the GHG savings provided through avoided emissions. The Irish scenarios (S1 – S4) included the GHG emissions produced by the crop production process (grass silage), feedstock collection and transport, biogas production process, and digestate disposal. These emissions were mainly generated from the diesel fuel consumption of the machinery used and from the emissions generated in the combustion of biogas in the CHP unit. The GHG savings were divided between emissions avoided by displacing fossil fuels used for energy generation and avoided fugitive methane emissions from manure storage and manure application to land (30). The USA scenarios (S5 – S7) considered the GHG emissions produced from the production of feedstock, the feedstock transportation, feedstock preparation for anaerobic digestion, the separation of by-products, and the combustion of biogas in the CHP unit. The GHG savings were based on the avoided emissions from the displacement of chemical fertiliser through the use of digestate as biofertiliser, and from the emissions avoided by displacing fossil fuels used by recycling the heat to the AD process in the form of steam (31).

3.3 Results and Discussion

3.3.1 Process variation and the effect on abatement costs for on-farm AD

Based on the assumptions for both the Irish and US scenarios, the TEA and LCA results reported in each study were used to construct an abatement curve for on-farm AD. The abatement cost of each scenario was obtained as shown in Table 3-10 by using the IPCC methodology shown in Equation 3.2 and a discount rate of 4% for the discounted lifetime abatement in guidance with the Irish Public Spending Code (65). The NPV and net annual GHG savings (t CO_{2eq} a^{-1}) were obtained from the TEA and LCA results reported in each study. Box 3-1 shows in detail the calculations of the abatement cost. A partial approach was selected to present the data. The resulting abatement curve, shown in Figure 3-2, shows that scenarios S2 to S4 have a negative cost of abatement, making them economically viable as mitigation options, whilst scenarios S1, S5, S6, and S7 have positive abatement costs indicating that they are high-cost abatement solutions.

Table 3-10 Assessment of abatement cost and Net GHG abatement for different on-farm AD scenarios.

Scenario	**Net GHG abatement (tCO_{2eq} a^{-1})**	**Lifetime of the project (Years)**	**NPV for lifetime of the project (€)**	**Source**	**Discounted Lifetime Abatement[d] (tCO_{2eq})**	**Abatement Cost (€ per tCO_{2eq})**
S1	45	20	-26758[b]	(30)	609	44
S2	88	20	67339[b]		1192	-56
S3	130	20	171168[b]		1773	-97
S4	173	20	275006[b]		2354	-117
S5	599[a]	30	-181076[c]	(31)	10358	17
S6	446[a]	30	-197932[c]		7713	26
S7	421[a]	30	-572124[c]		7273	79

a – Values were obtained by multiplying the GHG emissions reported in the study (kg CO_{2eq} kWh^{-1}) by the annual energy generated based on the system capacity of 950kW_e with an 85% annual operating capacity (7446 hrs a^{-1}).

b- A discount rate of 5% was used for financing, the tax rate was not considered as part of the calculations of the NPV.

c- An exchange rate of 0.85 USD $€^{-1}$ was used for the NPV values reported in the study to convert values from USD to euro. A discount rate of 7.5% was used for financing while a 39% tax rate was used for income.

d- Based on a discount rate for GHG emissions of 4 %.

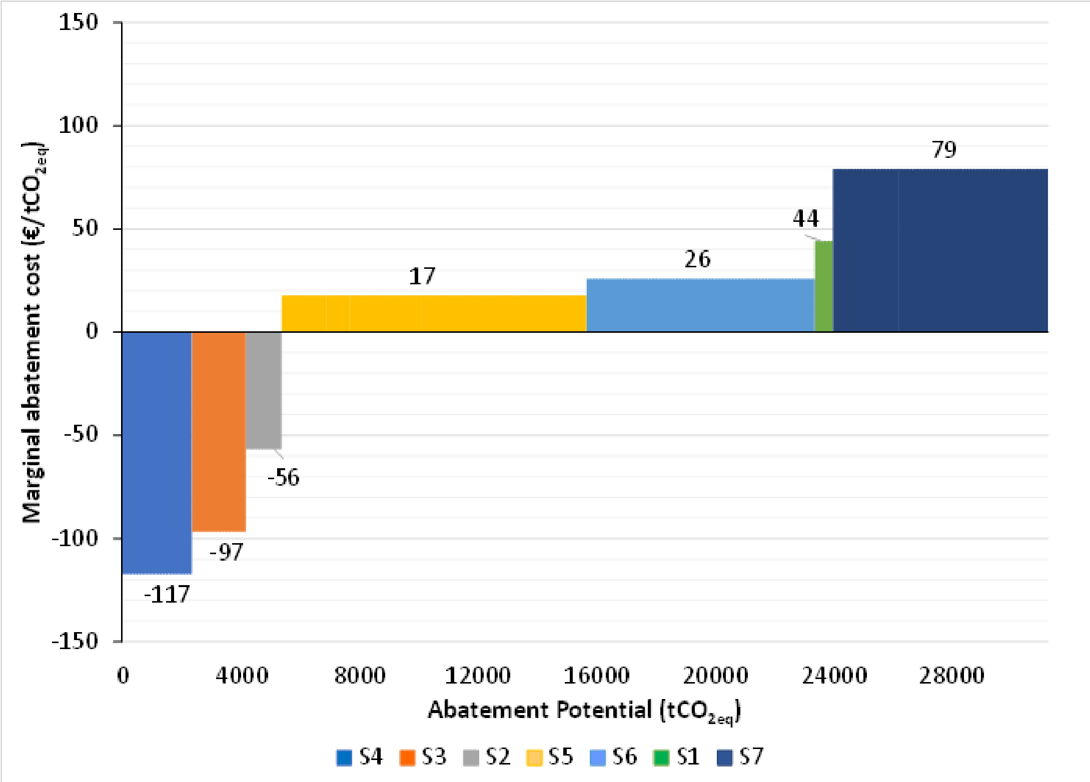

Figure 3-2 Abatement Cost Curve for small and medium scale on-farm AD systems. Small-scale scenarios S1 to S4 were based on Irish dairy farms with different herd sizes (S1-100, S2-150, S3-200, S4-250) utilizing grass silage and slurry as feedstocks. Medium-scale scenarios S5 to S7 were based on US beef farms with different types of feedstocks (S5- Corn Husk, S6-Rye, S7-Wheat) being co-digested with beef slurry.

Box 3-1. Calculation for the Abatement Cost

Ireland Scenario 1

Discounted Lifetime abatement

A discount rate of 4% for GHG emissions was assumed for the calculation of the discounted lifetime abatement. A period of 20 years based on the lifetime of the project was assumed. DAt is the discounted annual abatement in year t and calculated as show in Equation 3-3.

- $DA_1 = \frac{45}{(1+0.04)^1} = \frac{45}{1.04} = 43.12$ t CO_2 eq.
- $DA_2 = \frac{45}{(1+0.04)^2} = \frac{45}{1.08} = 41.46$ t CO_2 eq.
- .
- $DA_{20} = \frac{45}{(1+0.04)^{20}} = \frac{45}{2.19} = 20.47$ t CO_2 eq.

The total project abatement equals the sum of the discounted annual abatement.

- $DLA = 43.12 + 41.46 + \cdots + 20.47 = 609.47$ tCO_{2eq}.

Abatement cost

Using both the NPV reported by the study and the sum of the discounted abatement, the abatement cost curve was calculated using the IPCC methodology in Equation 3-2.

- $Abatement\ Cost = \frac{-(-26758)}{609.47} = 43.9$ € per tCO_{2eq}.

It is apparent from the results obtained in Figure 3-2 that the abatement cost of on-farm AD can fluctuate based on the scale of the system, the processes considered, and the system boundary applied for the calculation of the abatement cost. This is evident in scenarios S1 to S7 where the abatement cost ranged between -117 to +79 € tCO_{2eq}^{-1}, in comparison to the values presented in the Irish Climate Action Plan (Table 3-1) of 115 and 280 € tCO_{2eq}^{-1} for biogas to heat and power and biomethane, respectively (20). The assumptions selected for each study and the system boundary considered determine the overall result of the financial viability and the environmental mitigation of the system. Scenarios evaluated in the Climate Action Plan considered large-scale AD scenarios in which the GHG savings came mainly from displacing fossil fuels and the income was derived from the sale of the energy generated. The income for the biogas to heat and power scenario was generated from the sale of the energy produced set between 6 and 8 c€ kWh^{-1} and from the refit tariff of 14 c€ kWh^{-1}. The biomethane scenario only considered the income derived from the sale of the upgraded gas as biomethane at 3.5 c€ kWh^{-1}. It is unclear to the authors how the cost per tonne of CO_2 abated was calculated for each scenario as there is not enough insight on the methodology that was used to calculate the cost of each measure in the Climate Action Plan analysis.

For the scenarios considered in this paper for Ireland (S1 – S4) and the USA (S5 – S7), the system boundary selected for both TEA and LCA considered additional sources of income and GHG savings which were likely not considered by the analysis completed for the Climate Action Plan and may result in a lower cost of abatement. These include GHG savings from avoided fugitive methane emissions from manure storage and manure application to land and avoided emissions from the displacement of chemical fertiliser from the use of digestate as biofertiliser. In the case of revenues, these include the sale of heat in district heating networks; incentives from the management of by-products from digestate; and the offset of current heat and/or electricity costs at the farm. When incentives are included for the calculation of the abatement cost, it allows investors, the system operators, and policy makers, to see the magnitude of mitigation that each technology can achieve, as well as the economic performance of the system from the perspective of the system operator.

In the case of the scenarios for Ireland (S1-S4), more sources of revenues were considered (incentives, sale of heat produced, cost-savings from displaced energy) which resulted in a lower cost of abatement as the additional sources of income resulted in a positive NPV in comparison to the scenarios for the USA (S5-S7) that considered fewer sources of revenue (tax credit incentives) and additional costs (feedstock acquisition cost and taxes) which resulted in a negative NPV. The LCA of both studies considered similar sources of GHG emissions. In the US scenarios, the GHG emissions savings included for displacing synthetic fertiliser with digestate (as a biofertiliser) which resulted in greater mitigation owing to the extended system boundary in comparison to the Irish scenarios. The Irish scenarios only considered the GHG savings from the avoided fugitive methane emissions from manure storage and manure application to land. The system boundary differs between each study assessed and can vary from case to case based on the methodology used for the calculation of the TEA and LCA. This will alter the abatement cost which makes selecting a single point value to represent a mitigation technology difficult.

MACCs are a standard policy tool to assess the cost-effectiveness of mitigation options in a simplified and straightforward manner; however, the MACC results for certain technologies may present a single average cost that does not account for system variation, which ultimately may affect the abatement cost and the abatement potential of a mitigation technology. In particular, MACC analyses that use a partial approach have shortcomings that include a lack of disclosure of the input data assumptions selected for the calculations, the lack of consideration of interdependencies and interactions between variables, and the limited representation of uncertainty (66). These shortcomings can be a result of the amount of data required for the construction of the curve itself and the methodology selected for the calculation.

3.3.2 Integration of uncertainty analysis for the calculation of the abatement cost

Recent MACC values in other sectors have started to consider the representation of uncertainty during the construction of MACCs to provide a more transparent methodology where the cost and abatement potentials are compared (67–69). To carry out this methodology allowing for uncertainty, the single data points used in the construction of the curve need to be sampled from probability distributions, which in most cases can be performed using Monte Carlo simulations. However, incorporating various uncertainties may complicate the overall modelling of the abatement cost and potential, so it is recommended only to include the uncertainties of the input parameters that directly affect these values; these parameters can be obtained with a sensitivity analysis. In particular, the discount rate selected is a parameter that needs to be assessed in the sensitivity and uncertainty analysis as it affects both the calculations of the abatement cost and potential. Furthermore, given the shortcomings of the partial approach, the inclusion of uncertainty analysis will improve the robustness of the results illustrated in MACC by providing the potential range of abatement and abatement costs the mitigation technology provides.

3.3.3 Inclusion of economic diversification and the environmental benefits of on-farm AD

Only a handful of TEAs reviewed recognised two or more of the additional financial benefits of on-farm AD which may include the income from the sale of biofertiliser and co-products, the reduction of energy costs (for farm equipment, lighting, heating) and the reduction in chemical fertiliser use (24,31,32). Including more inputs and outputs in the system boundary provides a more representative methodology that can include possible additional financial benefits of the technology and provide a more realistic estimate of the viability of on-farm AD.

A recent TEA by González-Arias et al. (70) found that biogas plants with a digester size of 100 and 250 m^3 were unprofitable in comparison to larger biomethane production plants where the only revenue considered was the sale of biomethane (which depends on subsidies and incentives available). However, the same study did acknowledge that the profitability of small plants can be improved by considering other revenue streams where waste is converted into value-added materials and energy. Furthermore, new approaches for on-farm AD systems may provide extra revenues that can improve profitability by expanding the system boundary to include additional processes. Examples of this can be seen in biorefineries for isobutene and xylo-oligosaccharides evaluated by Lopes et al. (71) or the use of CO_2 produced as a by-product of AD for tomatoes cultivation in greenhouses evaluated by Oreggioni et al. (72) which were both proven to be economically viable. Another source of income could be waste management fees by integrating bio-stabilised organic solid wastes diverted from landfills as feedstock to the anaerobic digestion process which could increase the financial viability of the system (73). The integration of such fees has also been explored in Ireland as part of the National Waste Management Plan, in which waste fees could be modulated for users in a "pay as you throw" scheme based on the amount of waste delivered to the waste management system (74). However, the acceptance of bio-stabilised waste as an additional feedstock by farm scale anaerobic digestion systems would need to be strict in accordance with all health and safety requirements, specifically those governing the operation of anaerobic digestion plants to avoid the unintended spread of pathogens (reference to CN9 and CN11 from DAFM) (75).

For LCAs, the main emissions savings considered for the calculation of the GHG emissions comes from the emissions avoided from manure management, displacement of farm energy demand and energy exported, and displacement of fertiliser as shown in Table 3-8. Although there are certain environmental improvements that are not linked to GHG emissions such as the odour reduction through the use of biofertiliser and the improvement of water quality by reducing eutrophication, these were not considered in any of the analyses (76). This environmental benefit of AD could also be included within the system boundary if the GHG emissions that would be produced by technologies used to treat such problems are included in the calculations within the system boundary. This could prove beneficial in order to compare scenarios where the environmental benefit of AD is applied as seen in a MACC produced for the UK Climate Committee [62]. This particular MACC considered the environmental mitigation of AD as part of the assumptions based on the treatment of livestock excreta that would otherwise be stored in slurry tanks or lagoons. Furthermore, integrating technologies such as pyrolysis could allow anaerobic digestion systems to offer atmospheric carbon removal services based on the production of biochar from digestate (77). This could provide an alternative use for excess digestate produced in the anaerobic digestion process, which might not be utilised entirely by the farm. If all possible financial benefits and environmental improvements are considered within the system boundary, a more representative abatement cost and mitigation potential of anaerobic digestion, and indeed any technology, can be obtained.

3.3.4 Limitations of work

As part of this work, Ireland was presented as an example region to compare the abatement cost previously calculated for on-farm anaerobic digestion in the Climate

Action Plan 2019 with two case studies which presented results of on-farm anaerobic digestion scenarios at different scales. The calculation of the abatement cost can vary based on the region of analysis, or the methodology selected in undertaking the MACC assessment. The data used in this work were explicitly obtained to compare the methodology and system boundary applied in different regions for the calculation of key parameters such as the NPV and emissions savings, which allow the identification of all the potential financial benefits and environmental improvements that anaerobic digestion can provide. The methodology in this work can be expanded to other regions to expand the current system boundary used for the calculation of the abatement cost of a technology, in this case, anaerobic digestion. This can aid the representation of the abatement cost of anaerobic digestion whilst accounting for externalities such as improved manure management practices which are not commonly represented in abatement cost curve analyses.

3.4 Conclusion

To assess the financial viability of on-farm anaerobic digestion, the key parameters to consider in a techno economic assessment (TEA) are the net present value (NPV), the internal rate of return (IRR), and the payback period. Likewise, to assess the environmental impact, the key consideration in a lifecycle assessment (LCA) for the GHG assessment is to include emissions savings from the displacement of fossil fuel from avoided energy use; the displacement of chemical fertiliser use on-farm; and the emissions avoided from manure management. Most of the literature reviewed provided results from a TEA and LCA but did not calculate the abatement cost based on the results of the TEA and LCA.

Within this study, the abatement cost was evaluated for seven different scenarios for on-farm anaerobic digestion at different scales (small and medium) based on literature case studies (which included clear definitions of the methodology used for the TEA and LCA). Each scenario considered different processes and boundaries for both TEA and LCA which provided a range of different values of abatement cost and potential. The abatement cost varied from -117 € tCO_{2eq}^{-1} to +79 € tCO_{2eq}^{-1} clearly indicating that the variables selected for the study have a significant influence on the results. Additionally, the scale of the on-farm AD system and the revenue streams considered influenced the results. Small on-farm AD systems that accounted for a larger number of revenue streams (Irish scenarios) had a better economic performance but lower abatement potential than larger systems (US scenarios) in the studies analysed which resulted in lower abatement costs. On the contrary, scenarios with larger on-farm AD systems achieved greater GHG mitigation owing to the increased system size despite the low economic performance of the systems. Including GHG emissions savings from the avoided use of fertiliser further reduced abatement costs in the US scenarios. As such, accounting for additional income and emission savings from co-benefits can reduce the abatement cost.

Considering different variables within a study has a substantial impact on the calculation of the cost and abatement potential of on-farm anaerobic digestion. The scale and processes considered within the analysis determine the overall result in terms of financial viability and environmental mitigation. The system boundary directly influences the processes considered and therefore influences the results of the calculation. In the scenarios assessed in this work, it was found that if the study considered additional sources of revenue streams and savings (therefore a larger number of processes) a lower abatement cost would be obtained. Furthermore, the methodology differs between each study, and the processes considered to calculate the cost and abatement can vary from case to case based on the methodology and assumptions of each study. Prior analyses which presented a single value for the abatement cost for on-farm AD may not be able to accurately capture this variability in the system boundary considered; the scale of the system; and the revenue streams considered.

References

1. European Commission. 2050 long-term strategy [Internet]. 2016. Available from: https://ec.europa.eu/clima/policies/strategies/2050_en

2. Pilzecker A, Fernandez R, Mandl N, Rigler E. Annual European Union greenhouse gas inventory 1990–2019 and inventory report 2021 — European Environment Agency [Internet]. European Environment Agency; 2021. Available from: https://www.eea.europa.eu/publications/annual-european-union-greenhouse-gas-inventory-2021

3. Aertsens J, De Nocker L, Gobin A. Valuing the carbon sequestration potential for European agriculture. Land use policy. 2013 Mar 1;31:584–94.

4. McEldowney J. EU agricultural policy and climate change [Internet]. European Parliament; 2020. Available from: https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/651922/EPRS_BRI(2020)651922_EN.pdf

5. Liebetrau J, O'Shea R, Wellisch M. Potential and utilization of manure to generate biogas in seven countries [Internet]. IEA Bioenergy; 2021. Available from: https://task37.ieabioenergy.com/files/daten-redaktion/download/Technical%20Brochures/Potential%20utilization_WEB_END_NEW_2.pdf

6. Smyth BM, Murphy JD, O'Brien CM. What is the energy balance of grass biomethane in Ireland and other temperate northern European climates? Renewable and Sustainable Energy Reviews. 2009 Dec 1;13(9):2349–60.

7. Auer A, Vande Burgt NH, Abram F, Barry G, Fenton O, Markey BK, et al. Agricultural anaerobic digestion power plants in Ireland and Germany: policy and practice. J Sci Food Agric [Internet]. 2017;97(3):719–23. Available from: https://go.exlibris.link/VB7J4SmS

8. Wall DM, O'Kiely P, Murphy JD. The potential for biomethane from grass and slurry to satisfy renewable energy targets. Bioresour Technol [Internet]. 2013;149:425–31. Available from: https://www.sciencedirect.com/science/article/pii/S0960852413015265

9. Manyi-Loh CE, Mamphweli SN, Meyer EL, Okoh AI, Makaka G, Simon M. Microbial Anaerobic Digestion (Bio-Digesters) as an Approach to the Decontamination of Animal Wastes in Pollution Control and the Generation of Renewable Energy. Int J Environ Res Public Health [Internet]. 2013;10(9):4390–417. Available from: https://www.mdpi.com/1660-4601/10/9/4390

10. Kvist T, Aryal N. Methane loss from commercially operating biogas upgrading plants. Waste Management [Internet]. 2019;87:295–300. Available from: https://www.sciencedirect.com/science/article/pii/S0956053X19300935

11. Liebetrau J, Clemens J, Cuhls C, Hafermann C. Methane emissions from biogas-producing facilities within the agricultural sector. Eng Life Sci [Internet]. 2010 [cited 2022 Dec 6];10(6):595–9. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/elsc.201000070?casa_token=McPVFCtGSxwAAAAA:igXy_XypY3X7X3k83pDalpwCqQE6zv-c3VWymWffITc3KOto6sIOjqFcvutf-zGQdfLQIVk6zzJfqQ

12. Scarlat N, Dallemand JF, Fahl F. Biogas: Developments and perspectives in Europe. Renew Energy [Internet]. 2018;129:457–72. Available from: https://www.sciencedirect.com/science/article/pii/S096014811830301X

13. Farghali M, Osman AI, Umetsu K, Rooney DW. Integration of biogas systems into a carbon zero and hydrogen economy: a review. Environ Chem Lett [Internet]. 2022;20(5):2853–927. Available from: https://doi.org/10.1007/s10311-022-01468-z

14. Lauer M. Methodology guideline on techno economic assessment (TEA). Generated in the framework of ThermalNet WP3B economics. Thermal Net TEA Methodology Guideline. 2008;

15. Krey V, Masera O, Blanford USA G, Bruckner T, Cooke R, Fisher-Vanden K, et al. Annex II: Metrics & Methodology. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. 2014;

16. Murthy GS. Life-Cycle Assessment. In: Bioenergy : principles and applications. Wiley-Blackwell; 2016. p. 521–43.

17. O'Brien D, Shalloo L, Crosson P, Donnellan T, Farrelly N, Finnan J, et al. An evaluation of the effect of greenhouse gas accounting methods on a marginal abatement cost curve for Irish agricultural greenhouse gas emissions. Environ Sci Policy [Internet]. 2014;39:107–18. Available from: http://www.sciencedirect.com/science/article/pii/S1462901113001780

18. MacLeod M, Moran D, Eory V, Rees RM, Barnes A, Topp CFE, et al. Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. Agric Syst [Internet]. 2010;103(4):198–209. Available from: https://www.sciencedirect.com/science/article/pii/S0308521X1000003X

19. Government of Ireland. Climate Action Plan 2019 [Internet]. 2019 [cited 2022 Jul 13]. Available from: https://www.gov.ie/en/publication/ccb2e0-the-climate-action-plan-2019/

20. Lanigan GJ, Donnellan T, Lanigan G, Hanrahan K, Paul C, Shalloo L, et al. An Analysis of Abatement Potential of Greenhouse Gas Emissions in Irish Agriculture 2021-2030 Prepared by the Teagasc Greenhouse Gas Working Group Authors. 2019;

21. McKinsey & Company. Pathways to a Low-Carbon Economy. Version 2 of the Global Greenhouse Gas Abatement Cost Curve. [Internet]. 2009. Available from: https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/Sustainability/Our%20Insights/Pathways%20to%20a%20low%20carbon%20economy/Pathways%20to%20a%20low%20carbon%20economy.pdf

22. McKinsey & Company. Impact of the financial crisis on carbon economics. Version 2.1 of the Global Greenhouse Gas Abatement Cost Curve. [Internet]. 2010. Available from: https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/Sustainability/Our%20Insights/Impact%20of%20the%20financial%20crisis%20on%20carbon%20economics%20Version%2021/Impact%20of%20the%20financial%20crisis%20on%20carbon%20economics%20Version%2021.pdf

23. Rajendran K, Murthy GS. Techno-economic and life cycle assessments of anaerobic digestion – A review. Biocatal Agric Biotechnol. 2019 Jul 1;20:101207.

24. Khan EU, Mainali B, Martin A, Silveira S. Techno-economic analysis of small scale biogas based polygeneration systems: Bangladesh case study. Sustainable Energy Technologies and Assessments. 2014 Sep 1;7:68–78.

25. Wresta A, Andriani D, Saepudin A, Sudibyo H. Economic Analysis of Cow Manure Biogas as Energy Source for Electricity Power Generation in Small Scale Ranch. Energy Procedia [Internet]. 2015;68:122–31. Available from: https://www.sciencedirect.com/science/article/pii/S1876610215005469

26. Imeni SM, Puy N, Ovejero J, Busquets AM, Bartroli J, Pelaz L, et al. Techno-Economic Assessment of Anaerobic Co-digestion of Cattle Manure and Wheat Straw (Raw and Pre-treated) at Small to Medium Dairy Cattle Farms. Waste Biomass Valorization [Internet]. 2020;11(8):4035–51. Available from: https://doi.org/10.1007/s12649-019-00728-4

27. Mostafa Imeni S, Pelaz L, Corchado-Lopo C, Maria Busquets A, Ponsá S, Colón J. Techno-economic assessment of anaerobic co-digestion of livestock manure and cheese whey (Cow, Goat & Sheep) at small to medium dairy farms. Bioresour Technol [Internet]. 2019;291:121872. Available from: https://www.sciencedirect.com/science/article/pii/S0960852419311022

28. Perta ES di, Cervelli E, Campagna MP di, Pindozzi S. From biogas to biomethane: Techno-economic analysis of an anaerobic digestion power plant in a cattle/buffalo farm in central Italy. Journal of Agricultural Engineering [Internet]. 2019;50(3). Available from: https://doaj.org

29. Villarroel-Schneider J, Mainali B, Martí-Herrero J, Malmquist A, Martin A, Alejo L. Biogas based polygeneration plant options utilizing dairy farms waste: A Bolivian case. Sustainable Energy Technologies and Assessments. 2020 Feb 1;37:100571.

30. O'Connor S, Ehimen E, Pillai SC, Lyons G, Bartlett J. Economic and Environmental Analysis of Small-Scale Anaerobic Digestion Plants on Irish Dairy Farms. Energies 2020, Vol 13, Page 637 [Internet]. 2020 Feb 3 [cited 2022 May 23];13(3):637. Available from: https://www.mdpi.com/1996-1073/13/3/637/htm

31. Aui A, Li W, Wright MM. Techno-economic and life cycle analysis of a farm-scale anaerobic digestion plant in Iowa. Waste Management [Internet].

2019;89:154–64. Available from: https://www.sciencedirect.com/science/article/pii/S0956053X19302260

32. Croxatto Vega G, Voogt J, Sohn J, Birkved M, Olsen SI. Assessing New Biotechnologies by Combining TEA and TM-LCA for an Efficient Use of Biomass Resources. Sustainability [Internet]. 2020;12(9):3676. Available from: https://www.mdpi.com/2071-1050/12/9/3676

33. Nayal FS, Mammadov A, Ciliz N. Environmental assessment of energy generation from agricultural and farm waste through anaerobic digestion. J Environ Manage [Internet]. 2016;184:389–99. Available from: https://www.sciencedirect.com/science/article/pii/S0301479716307216

34. Pardo G, Moral R, del Prado A. SIMSWASTE-AD - A modelling framework for the environmental assessment of agricultural waste management strategies: Anaerobic digestion. Science of The Total Environment. 2017 Jan 1;574:806–17.

35. Adams PWR, McManus MC. Characterisation and variability of greenhouse gas emissions from biomethane production via anaerobic digestion of maize. J Clean Prod [Internet]. 2019;218:529–42. Available from: https://www.sciencedirect.com/science/article/pii/S0959652618339532

36. Jones P, Salter A. Modelling the economics of farm-based anaerobic digestion in a UK whole-farm context. Energy Policy. 2013 Nov 1;62:215–25.

37. Noun Project. Noun Project: Free Icons & Stock Photos for Everything [Internet]. 2021. Available from: https://thenounproject.com/

38. Browne J, Nizami AS, Thamsiriroj T, Murphy JD. Assessing the cost of biofuel production with increasing penetration of the transport fuel market: A case study of gaseous biomethane in Ireland. Renewable and Sustainable Energy Reviews. 2011 Dec 1;15(9):4537–47.

39. AgSTAR. Project Development Handbook. A Handbook for Developing Anaerobic Digestion/Biogas Systems on Farms in the United States [Internet]. EPA; 2014. Available from: https://www.epa.gov/sites/production/files/2014-12/documents/agstar-handbook.pdf#page=81

40. Gebrezgabher SA, Meuwissen MPM, Oude Lansink AGJM, Gebrezgabher SA, Meuwissen MPM, Oude Lansink AGJM. Costs of Producing Biogas at Dairy

Farms in The Netherlands. 2010; Available from: https://ageconsearch.umn.edu/record/91139

41. Tolessa A, Louw TM, Goosen NJ. Probabilistic techno-economic assessment of anaerobic digestion predicts economic benefits to smallholder farmers with quantifiable certainty. Waste Management [Internet]. 2022;138:8–18. Available from: https://www.sciencedirect.com/science/article/pii/S0956053X21005845

42. Tan WE, Liew PY, Tan LS, Woon KS, Mohammad Rozali NE, Ho WS, et al. Life Cycle Assessment and Techno-Economic Analysis for Anaerobic Digestion as Cow Manure Management System. Energies (Basel) [Internet]. 2022;15(24):9586. Available from: https://www.mdpi.com/1996-1073/15/24/9586

43. Herbes C, Rilling B, Ringel M. Policy frameworks and voluntary markets for biomethane – How do different policies influence providers' product strategies? Energy Policy [Internet]. 2021;153:112292. Available from: https://www.sciencedirect.com/science/article/pii/S0301421521001610

44. Pablo-Romero M del P, Sánchez-Braza A, Salvador-Ponce J, Sánchez-Labrador N. An overview of feed-in tariffs, premiums and tenders to promote electricity from biogas in the EU-28. Renewable and Sustainable Energy Reviews [Internet]. 2017;73:1366–79. Available from: https://www.sciencedirect.com/science/article/pii/S1364032117301429

45. RES Legal. Legal sources on renewable energy. Renewable energy policy database and support [Internet]. 2021. Available from: http://www.res-legal.eu/search-by-country/germany/single/s/res-e/t/promotion/aid/feed-in-tariff-eeg-feed-in-tariff/lastp/135/

46. SEAI. Support Scheme for Renewable Heat [Internet]. 2023. Available from: https://www.seai.ie/business-and-public-sector/business-grants-and-supports/support-scheme-renewable-heat/

47. Government of UK. Non-domestic Renewable Heat Incentive (RHI) [Internet]. 2023 [cited 2023 Jun 22]. Available from: https://www.gov.uk/non-domestic-renewable-heat-incentive

48. Chavas JP, Kim K. Economies of diversification: A generalization and decomposition of economies of scope. Int J Prod Econ [Internet]. 2010;126(2):229–

35. Available from:
https://www.sciencedirect.com/science/article/pii/S0925527310000927

49. Zacharof MP, Mandale SJ, Williams PM, Lovitt RW. Nanofiltration of treated digested agricultural wastewater for recovery of carboxylic acids. J Clean Prod [Internet]. 2016;112:4749–61. Available from: https://www.sciencedirect.com/science/article/pii/S0959652615008835

50. Vasco-Correa J, Khanal S, Manandhar A, Shah A. Anaerobic digestion for bioenergy production: Global status, environmental and techno-economic implications, and government policies. Bioresour Technol [Internet]. 2018;247:1015–26. Available from: https://www.sciencedirect.com/science/article/pii/S0960852417315456

51. Rajendran K, O’Gallachoir B, Murphy JD. The combined role of policy and incentives in promoting cost efficient decarbonisation of energy: A case study for biomethane. J Clean Prod. 2019 May 10;219:278–90.

52. Saltelli A, Aleksankina K, Becker W, Fennell P, Ferretti F, Holst N, et al. Why so many published sensitivity analyses are false: A systematic review of sensitivity analysis practices. Environmental Modelling & Software. 2019 Apr 1;114:29–39.

53. Jovanović P. Application of sensitivity analysis in investment project evaluation under uncertainty and risk. International Journal of Project Management [Internet]. 1999;17(4):217–22. Available from: https://www.sciencedirect.com/science/article/pii/S0263786398000350

54. Fuess LT, Zaiat M. Economics of anaerobic digestion for processing sugarcane vinasse: Applying sensitivity analysis to increase process profitability in diversified biogas applications. Process Safety and Environmental Protection. 2018 Apr 1;115:27–37.

55. Teymoori Hamzehkolaei F, Amjady N. A techno-economic assessment for replacement of conventional fossil fuel based technologies in animal farms with biogas fueled CHP units. Renew Energy [Internet]. 2018;118:602–14. Available from: https://www.sciencedirect.com/science/article/pii/S0960148117311552

56. Short W, Packey D, Holt T. A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies. NASA STI/Recon Technical Report N [Internet]. 1995;95. Available from: https://www.researchgate.net/publication/253763510_A_Manual_for_the_Economic_Evaluation_of_Energy_Efficiency_and_Renewable_Energy_Technologies

57. European Commission. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) [Internet]. 2018 [cited 2022 Jul 21]. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC

58. Czyrnek-Delêtre MM, Smyth BM, Murphy JD. Beyond carbon and energy: The challenge in setting guidelines for life cycle assessment of biofuel systems. Renew Energy [Internet]. 2017;105:436–48. Available from: https://www.sciencedirect.com/science/article/pii/S0960148116310126

59. Sathaye JA, Meyers S. Greenhouse Gas Mitigation Assessment: A Guidebook [Internet]. Environmental Science and Technology Library. Springer Netherlands; 1995. Available from: https://www.springer.com/gp/book/9780792337812

60. Eory V, Topp CFE, Moran D. Multiple-pollutant cost-effectiveness of greenhouse gas mitigation measures in the UK agriculture. Environ Sci Policy. 2013 Mar 1;27:55–67.

61. Bank W. Low-Carbon Development for Mexico. Energy Sector Management assistance Program. [Internet]. ESMAP; 2010. Available from: https://openknowledge.worldbank.org/handle/10986/17527

62. Eory V, MacLeod M, Topp CFE. Review and update of the UK agriculture marginal abatement cost curves (SRUC, Ricardo Energy) [Internet]. Climate Change Committee; 2015. Available from: https://www.theccc.org.uk/publication/scotlands-rural-collage-sruc-ricardo-energy-and-environment-2015-review-and-update-of-the-uk-agriculture-macc-to-assess-abatement-potential-for-the-fifth-carbon-budget-period-and-to-2050/

63. Union E. S.I. No. 605/2017 - European Union (Good Agricultural Practice for Protection of Waters) Regulations 2017 [Internet]. Dublin, Ireland: Stationery

Office; 2017. Available from:
https://www.irishstatutebook.ie/eli/2017/si/605/made/en/print

64. USDA. Beef Feedlot Industry Manual. The United States Department of Agriculture, Animal and Plant Health Inspection Service, Veterinary Services; 2011.

65. Public Spending Code. Supplementary Guidance - Measuring & Valuing Changes in Greenhouse Gas Emissions in Economic Appraisal [Internet]. Dublin; 2019 [cited 2022 Aug 5]. Available from: https://www.gov.ie/en/publication/public-spending-code/

66. Kesicki F, Ekins P. Marginal abatement cost curves: a call for caution. Climate Policy [Internet]. 2012;12(2):219–36. Available from: http://www.proquest.com/docview/1321412769/abstract/A1416703CBDF4947PQ/1

67. Peng BB, Xu JH, Fan Y. Modeling uncertainty in estimation of carbon dioxide abatement costs of energy-saving technologies for passenger cars in China. Energy Policy [Internet]. 2018;113:306–19. Available from: https://www.sciencedirect.com/science/article/pii/S0301421517307486

68. Sjöstrand K, Lindhe A, Söderqvist T, Dahlqvist P, Rosén L. Marginal Abatement Cost Curves for Water Scarcity Mitigation under Uncertainty. Water Resources Management [Internet]. 2019;33(12):4335–49. Available from: https://doi.org/10.1007/s11269-019-02376-8

69. Dunant CF, Skelton ACH, Drewniok MP, Cullen JM, Allwood JM. A marginal abatement cost curve for material efficiency accounting for uncertainty. Resour Conserv Recycl [Internet]. 2019;144:39–47. Available from: https://www.sciencedirect.com/science/article/pii/S0921344919300229

70. González-Arias J, Baena-Moreno FM, Gonzalez-Castaño M, Arellano-García H, Lichtfouse E, Zhang Z. Unprofitability of small biogas plants without subsidies in the Brandenburg region. Environ Chem Lett [Internet]. 2021;19(2):1823–9. Available from: https://doi.org/10.1007/s10311-020-01175-7

71. Lopes TF, Carvalheiro F, Duarte LC, Gírio F, Quintero JA, Aroca G. Techno-economic and life-cycle assessments of small-scale biorefineries for isobutene and xylo-oligosaccharides production: a comparative study in Portugal and Chile. Biofuels, Bioproducts and Biorefining [Internet]. 2019 Sep 1 [cited 2023 Jun

28];13(5):1321–32. Available from: https://onlinelibrary.wiley.com/doi/full/10.1002/bbb.2036

72. Oreggioni GD, Luberti M, Tassou SA. Agricultural greenhouse CO2 utilization in anaerobic-digestion-based biomethane production plants: A techno-economic and environmental assessment and comparison with CO2 geological storage. Appl Energy. 2019 May 15;242:1753–66.

73. Al-Wahaibi A, Osman AI, Al-Muhtaseb AH, Alqaisi O, Baawain M, Fawzy S, et al. Techno-economic evaluation of biogas production from food waste via anaerobic digestion. Sci Rep. 2020;10(1):15719.

74. Regional Waste Management Planning Offices. The National Waste Management Plan for a Circular Economy is Ireland's framework for the prevention and management of waste. [Internet]. 2023. Available from: https://www.mywaste.ie/wp-content/uploads/2023/05/SRWMO-National-Waste-Management-Plan-for-a-Circular-Economy-Volume-IV-Supporting-Documentation-AW-Onscreen.pdf

75. Government of Ireland. Conditions for Animal By Product Processing Operations [Internet]. 2019. Available from: https://www.gov.ie/en/publication/8c7cd-conditions-for-abp-processing-operations/

76. Global Methane Initiative. Successful Applications of Anaerobic Digestion from Across the World [Internet]. 2013 [cited 2023 Jun 28]. Available from: https://www.globalmethane.org/documents/gmi%20benefits%20report.pdf

77. Fawzy S, Osman AI, Mehta N, Moran D, Al-Muhtaseb AH, Rooney DW. Atmospheric carbon removal via industrial biochar systems: A techno-economic-environmental study. J Clean Prod [Internet]. 2022;371:133660. Available from: https://www.sciencedirect.com/science/article/pii/S0959652622032383

4 Assessing the cost variability of emissions abatement in small-scale on-farm anaerobic digestion

Assessing the cost variability of emissions abatement in small-scale on-farm anaerobic digestion.

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Abstract:

Agriculture is considered a hard to abate sector in which 2050 net-zero greenhouse gas (GHG) emissions targets will be challenging. Anaerobic digestion is a technology that can reduce agricultural emissions whilst producing renewable energy and a biofertiliser. In Ireland this technology was previously evaluated to be a high cost of abatement solution. However, it is not clear if the potential variations in anaerobic digestion systems were accounted for in these analyses; scale, plant design, technology, feedstock and biogas end-use differ between systems and can directly impact abatement costs. This study assesses different biogas end-use options (generation of heat, electricity and biomethane) and varying farm sizes for on-farm anaerobic digestion systems digesting grass silage and cattle slurry feedstocks. To evaluate and compare each biogas end-use for the varying farm sizes, the abatement cost and potential was obtained based on the net present value (NPV) and the total discounted GHG emissions for each system configuration. The abatement cost of the on-farm anaerobic digestion systems assessed varied between -7 € tCO_{2eq}^{-1} to 816 € tCO_{2eq}^{-1}. For a farm with 185 dairy cows, the integration of anaerobic digestion with the use of a boiler to produce heat sold through a district heating network was found to be a financially viable option. Biogas upgrading to produce biomethane was not financially viable due to the high operational and capital costs of small-scale upgrading systems. A key result of the analysis shows that if a single input variable is changed within the system boundary, the financial and environmental performance of a system can be significantly changed. For example, an increase in tariffs and biomethane sale prices can substantially improve the financial viability from +72 € tCO_{2eq}^{-1} to -227 € tCO_{2eq}^{-1}. Similarly, a higher cost for grass silage feedstock (€ 43

per tonne) will unfavourably impact the abatement cost; raising it from -7 € tCO_{2eq}^{-1} to 492 € tCO_{2eq}^{-1}.

Keywords: Anaerobic Digestion; Economic performance; Techno-economic analysis; GHG assessment; Abatement Cost.

4.1 Introduction

The reduction of greenhouse gas (GHG) emissions has become a priority for the European Union (EU) due to the increased threat of global warming. Through environmental policies, the EU aims to achieve a net-zero GHG economy and be climate-neutral by 2050 (1). The agricultural sector has the second highest GHG emissions over the combined 27 EU member States, totalling 15.6%, as per Figure 4-1 (1). Only electricity production had higher associated GHG emissions within the EU's primary economic sectors (1). The GHG emissions from agriculture vary by country and are based on the type of products and practices used to produce farm-based goods. In Ireland, the agricultural sector is one of the main contributors to the country's economic growth (2). This sector contributes a much higher percentage of GHG emissions (38.5%) relative to the EU (15.6%) (3). Thus, agriculture presents a serious decarbonisation challenge in Ireland and must be carefully considered in future national strategies when accounting for the EU climate mitigation policies.

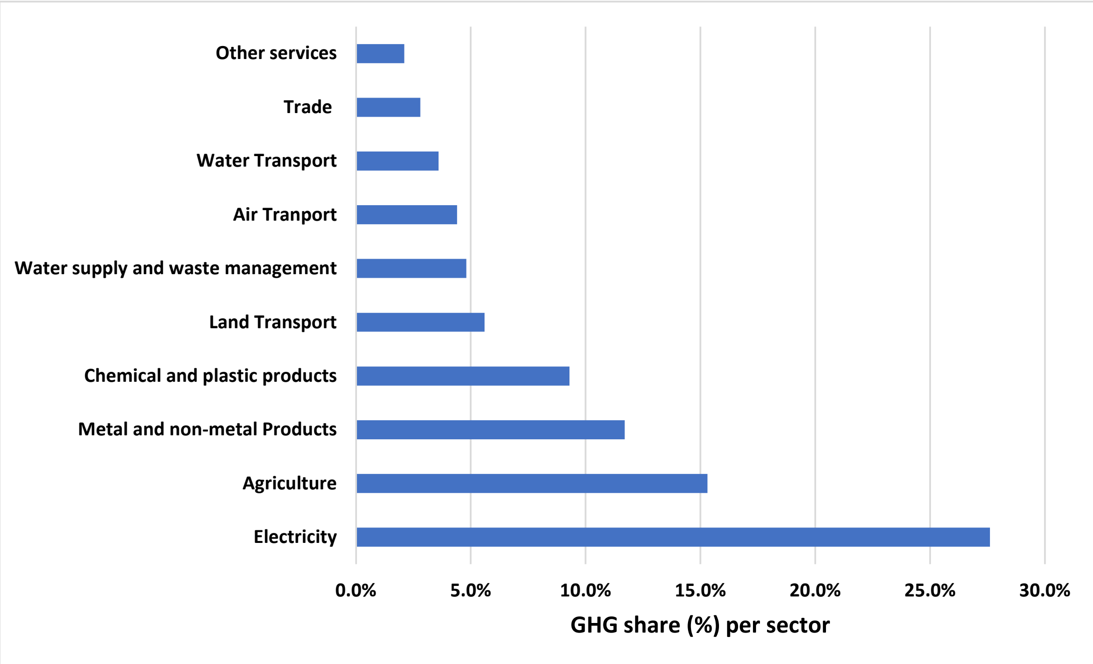

Figure 4-1 Top 10 greenhouse gas (GHG) emissions share by sector (%) within the main economic sectors of the EU-27 for the year 2019. Adapted from Giannakis & Zittis (1).

Agriculture is deemed a hard to abate sector (4,5); methane emissions from enteric fermentation are difficult to mitigate, and manure management is problematic when manure is stored in open tanks which leads to fugitive methane emissions, eutrophication, and ground water contamination in wet climates (6). Methods are sought to reduce GHG emissions, minimise waste production and improve manure and livestock management (7). Options may include a reduction in the herd size effected through a reduction in consumer intake of meat and dairy products, and/or conversion of arable land to woodland areas or permanent pastures to sequester carbon into the soil (8). Additional options include integrating mitigation technologies such as anaerobic digestion (AD) that reduce GHG emissions in agriculture whilst providing for enhanced manure management (9).

Techno-economic analyses (TEAs) are used to assess the financial performance of a project (10). While a life-cycle assessments (LCAs) can be used to assess the material, energy and environmental impact of a project during the life cycle of the process (11). Different impact categories can be evaluated such as climate change, ozone depletion, particulate matter, eutrophication, and smog formation (12). For the purpose of this study, the focus will be on the sub-category of climate change that measures the GHG emissions based on a defined system boundary. By combining the results from both analyses, it is possible to calculate the abatement cost and abatement potential of a project. Based on the cost and potential abatement of a technology, the projects can be compared across a marginal abatement cost curve (MACC) by comparing and ordering the cost per unit of CO2eq abated (on the y-axis) and the quantity of GHG emissions mitigated (on the x-axis) from left to right as the cost-effectiveness decreases (13).

In 2019, a MACC was developed to evaluate the adoption of different technologies across all sectors of the Irish economy to reach the decarbonisation target of a 30% reduction in total GHG emissions by 2030 as set out in the Irish Climate Action Plan (14). AD was evaluated as a potential mitigation option within the agriculture and forestry sectors, but it was found to be a high cost of abatement solution. Two options were assessed, generation of heat and electricity from biogas (115 € tCO_{2eq}^{-1} abated) and the production of renewable heat from biomethane (280 € tCO_{2eq}^{-1} abated) (15). Both scenarios encompass single values that may not capture the potential variation of AD systems in terms of scale, design, technology, feedstock, and biogas end-use. The development of a customised enviro-economic tool that calculates key TEA and the GHG emissions results of AD systems could potentially provide an enhanced method to calculate abatement costs.

This study aims to assess different biogas end-use options (generation of heat, electricity and biomethane for transport fuel) for on-farm AD systems through a combined enviro-economic tool (that incorporates both TEA and GHG emissions assessment) to develop abatement cost curves. Furthermore, to assess different biogas end-uses, the tool will evaluate different scenarios that correspond to various AD system configurations and different herd sizes based on the median farm size in Ireland. The financial viability and potential carbon abatement of each scenario will be assessed and used to obtain individual abatement costs. Comparing scenarios through their abatement costs will allow for the identification of the most economically feasible scenarios that provide the best carbon mitigation, corresponding to a specific abatement cost for farmers and policy makers. Four specific objectives for this study are outlined below:

i. Generate scenarios for on-farm AD that incorporate different configurations in terms of biogas end-use and varying farm size;
ii. Calculate the key parameters of a TEA and the GHG emissions generated for the scenarios outlined;
iii. Calculate the abatement cost and the mitigation potential for each on-farm AD scenario;
iv. Assess the implications of changing the input variables in the calculation of abatement cost and illustrate the effect of changing the AD system boundary in terms of emissions savings.

4.2 Methodology

4.2.1 Biogas end-use configurations and scenario overview

A schematic representation of the pathways for biogas end-use in on-farm AD systems is presented in Figure 4-2. Four configurations for biogas end-use were selected for the analysis: 1) the generation of heat from a boiler (Boiler); 2) the generation of electricity and heat from a combined heat and power unit (CHP); 3) the production of biomethane via a biogas upgrading technology for use as a source of heat or transport fuel (UPG); and 4) the production of biomethane via biogas upgrading with the addition of a CHP unit (UPG + CHP) to provide heat and electricity to the AD process (to offset the need for purchasing electricity and gas externally). Furthermore, the digestate generated by the system was considered a valuable by-product as biofertiliser and a potential source of revenue.

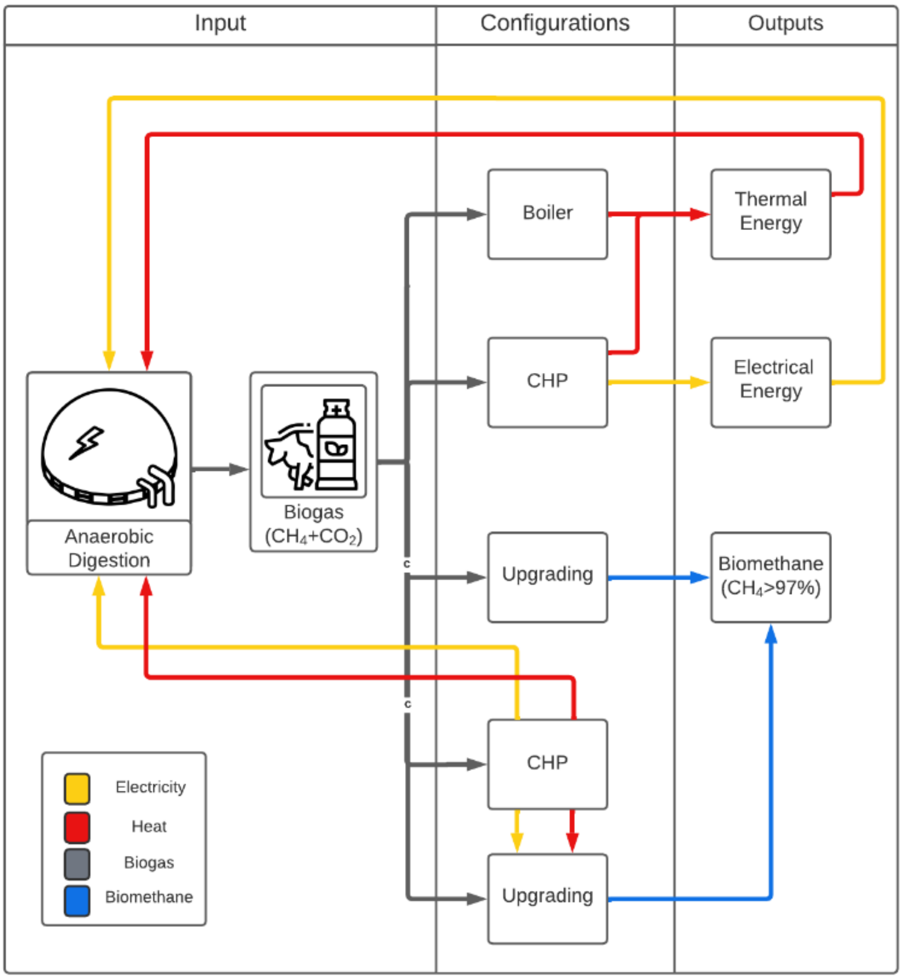

Figure 4-2 Process diagram for biogas end-use gas configurations for on-farm AD systems

To evaluate the effect of farm size on each biogas end-use, four hypothetical farm sizes were selected based on the median agricultural area of dairy farms in Ireland (16). The utilised agricultural area for dairy farms in Ireland ranges between four different distributions: less than 30 ha (13.2%); 30 to 50 ha (29.4%); 50 to 100 ha (43.7%), and greater than 100 ha (13.7%). Based on the average herd size for Ireland an average farmland area for each hypothetical farm was calculated as shown in Table 3-1. The herd size for each of the four hypothetical farm sizes was set as 40, 60, 100, and 185 dairy cows based on the average dairy cow herd size for dairy farms corresponding to the results from the Teagasc National Farm Survey (17). For each farm, the pasture area was calculated based on an average dairy stocking rate of 2.06 lu ha^{-1} (livestock units per hectare), while the remaining area was assumed to be used to cultivate grass silage (Table 4-1) (18). In total, sixteen different scenarios were selected to assess the financial viability and potential carbon abatement of on-farm AD systems through the enviro-economic tool based on the 4 different configurations outlined in Figure 4-2 (Boiler, CHP, UPG, UPG+CHP) for each of the 4 herd sizes (40, 60, 100, 185).

Table 4-1 Area distribution for each of the four hypothetical farm sizes.

Average Herd Size (Dairy Cows)	40	60	100	185
Farmland (ha)	27.8	44.4	72.9	136.2
Surplus Grass (ha)	8.4	15.3	24.4	46.4

The economic analysis for each scenario requires specific input information for the region of analysis including technical aspects of the AD process, costs associated with the feedstock, and revenues attributed to the products (biogas and biomethane) and by-products (biofertiliser, electricity, steam) generated. For each scenario, an economic analysis was carried out using an enviro-economic tool developed for this work in which the key indicators (NPV, IRR, and payback period) were obtained to compare their financial viability.

The methodology proposed in the EU Renewable Energy Directive (Recast RED-II) was used to calculate the net GHG emissions, with the inclusion of emissions savings from energy displacement (heat, electricity and transport fuel) and the displacement of synthetic fertiliser (19). This considers that the biofertiliser will displace the emissions generated from synthetic fertiliser production and the renewable energy produced will displace emissions from energy generated by fossil fuels (20). The emission factors and equations to calculate the emissions were based on the IPCC methodology (21). Using the economic and environmental results from the enviro-economic tool, an abatement cost curve was constructed based on the system configuration to compare the abatement cost and the potential magnitude of abatement in the different scenarios. The technical data used in the analysis presented was obtained from the work of O'Shea et. al (22–24), Allen et al. (25), and Long et al. (21).

4.2.2 Anaerobic digestion process modelling

Grass silage and slurry (typical biomass used for AD in Ireland) were considered when calculating the total resource of feedstocks available for the on-farm AD scenarios. Both cattle slurry (R_1^{CS}) and grass silage (R_2^{GS}) feedstock resources were calculated in terms of wet weight tonnes (t_{wwt}) per year. A detailed methodology of the calculations used for each of the feedstocks can be found in Appendix B.1.

The properties of slurry can fluctuate throughout the year based on the animal's diet and the stage of lactation which may result in a variable biogas yield (25). Additionally, the properties of grass as a feedstock vary depending on the region and method of cultivation. Examples of previous grass and slurry feedstocks used in AD trials can be found in Tables B-2 and B-3 of Appendix B.2. For the analysis of the hypothetical farms in this work, cattle slurry collected in autumn and grass silage sourced from the midlands of Ireland (1st cut grass and late-cut grass representing the 2nd cut) were selected for the co-digestion analysis (Table 4-2).

Table 4-2 Feedstock characteristics for grass silage and slurry. Adapted from Allen et al. (25).

Description	Cattle Slurry	Grass Silage 1st Cut	Grass Silage 2nd Cut
Total Solids (%wwt)	6.50	29.30	17.90
Volatile Solids (%wwt)	5.10	26.80	16.40
Ash Content (%wwt)	1.40	2.5	1.50
Volatile Solids/Total Solids (%)	78.50	91.70	92.00
Specific Methane Yield (LCH_4 $kgVS^{-1}$)	175.5	400	393
Nitrogen in Total Solids (%)	2.00	1.70	1.10
Methane Content (%)	56	53	53

The volumetric biogas production (V_{AD}) from the co-digestion of grass silage and cattle slurry was then calculated in cubic metres per annum (m^3 a^{-1}) based on the volatile solids content of the feedstock mixture. Detailed calculations of the volumetric biogas production can be found in the Appendix B.2. Methane leakage over the whole system was considered minimal at 2% accounting for each different configuration. Existing leakage on biogas systems ranges between 2 to 10% although based on prior literature the methane losses can be reduced with adequate digestate storage and no direct methane leaks occurring from the digester (26,27). Based on the methane leakage the gross biogas obtained was 98% of the total volumetric production of biogas (V_{AD}).

Electrical energy consumption (EC_{AD}) of the AD process was assumed to be 10 kWh/twwt per annum based on previous literature values (28–31). Based on the electrical energy consumption, the electricity demand of the AD process (ED_{AD}) was calculated in kWh/a using the mass of each feedstock (R_1^{CS}, R_2^{GS}, t_{wwt} a^{-1}) used in the AD process (Equation 4-1).

Equation 4-1 Electrical demand of the AD process.

$$ED_{AD}\left(\frac{\text{kWh}}{\text{a}}\right) = EC_{AD} * (R_1^{CS} + R_2^{GS})$$

To calculate the thermal demand of the AD process (TD_{AD}) in MJ a^{-1}, different parasitic demands of the AD process comprising of; the heat required for substrate heating, the fabric heat loss of the AD tank structure to the environment, and heat loss through evaporation inside the digester were considered for the total thermal demand. Detailed calculations of the thermal energy losses are based on prior work by O'Shea et al. (31) and are summarised in in the Appendix B.3.

4.2.3 Biogas end-uses

The first configuration for biogas end-use (as per Figure 4-2) assumes that the biogas will be burned in a boiler to generate heat for use in the immediate vicinity of the AD plant or in a district heating system (if one exists). District heating has been evaluated in Ireland as one option for local community heating schemes in smaller towns across Ireland as there are around 18,641 small areas with district heating potential (32). From these small areas around 311 have a heat density higher than 10,000 MWh km^{-1} which hold the best potential for district heating as systems with less heat density are considered not finically viable due to the construction price of a network (33). Although if small areas with a heat demand between 1,000 to 10,000 MWh km^{-1} were included in these heating schemes, district heating could provide 54% of the total heat demand of the small areas around Ireland.

The thermal energy generated was calculated based on a boiler efficiency (η_{Boiler}) of 90% which is common for natural gas boilers (24,34). The overall annual net heat output (HO_{Boiler}) was calculated based on the gross energy output of the AD process (EO_{AD}, MJ a^{-1}) and boiler efficiency (η_{Boiler}) considering that part of the heat is supplied to the AD process to cover the thermal demand (TD_{AD}, MJ a^{-1}) and then converted to kWh a^{-1} as shown in Equation 4-2. Detailed calculations of the sizing of the boiler unit can be found in the Appendix B.4.

Equation 4-2 Net heat output of the boiler configuration.

$$HO_{Boiler}\left(\frac{\text{kWh}}{\text{a}}\right) = \left((EO_{AD} * \eta_{Boiler}) - TD_{AD}\right)/3.6$$

The second configuration for biogas end-use assumes that the biogas will be used to generate heat and electricity in a CHP unit. The electricity and heat generated were calculated based on the average electrical efficiency (η_{ECHP}) of 35% and thermal efficiency (η_{TCHP}) of 50% for units with less than a 100kW_{el} output that are typically installed at small-scale systems (35–38). Based on the required electrical power of the scenarios a maximum CHP unit size of 70 kW_{el} was considered. The annual net electric output (EO_{CHP}) was calculated from the overall gross energy output of the AD process (EO_{AD}, MJ/a) and electric efficiency (η_{ECHP}) and converted to kWh/a considering that part of the electricity produced will be used to cover the electric demand of the AD process (ED_{AD}, kWh/a) (Equation 4-3). The overall net heat output was also calculated based on the AD gross energy output (EO_{AD}, MJ a^{-1}) based on the CHP thermal efficiency (η_{TCHP}); part of the heat is supplied to the AD process to cover the thermal demand (TD_{AD}, MJ a^{-1}). The net heat output is converted to units of kWh a^{-1} (Equation 4-4). Detailed calculations of the sizing of the CHP unit can be found in the Appendix B.4.

Equation 4-3 Net electric output of the boiler configuration.

$$EO_{CHP}\left(\frac{\text{kWh}}{\text{a}}\right) = \left((EO_{AD} * \eta_{ECHP})/3.6 - (ED_{AD})\right)$$

Equation 4 Net heat output of the boiler configuration.

$$HO_{CHP}\left(\frac{\text{kWh}}{\text{a}}\right) = \left((EO_{AD} * \eta_{TCHP}) - TD_{AD}\right)/3.6$$

For the biogas upgrading configuration, many technologies (water scrubbing, pressure swing adsorption, chemical/amine scrubbing, and membrane separation) are available for the removal of CO_2 from biogas to produce biomethane which can be directly injected into the gas network. A table with the average technical features for biogas upgrading technologies can be found in the Appendix B.5 (Table B-5). This scenario considers that all of the biogas produced (V_{AD}) is upgraded to biomethane using electricity from the electricity grid and natural gas for the boiler to obtain a higher revenue from the direct sale of biomethane.

For the scenarios with an upgrading configuration, water scrubbing (Table B-5) was selected as the upgrading technology as there have been previous small-scale systems that integrate this technology to upgrade to biomethane (39). The overall energy output of biomethane (EO_{UP}) was calculated in kWh/a based on the amount of methane recovered from the biogas production (V_{AD}, m^3 a^{-1}), accounting for an initial 6% methane in the off-gas from the water scrubbing upgrading process (CH_4Slip_{UP}, % Total CH_4 Production), with a calorific value of 35.7 MJ $Nm^3CH_4^{-1}$ (cv_{CH_4}) assuming a LHV of methane as 50 MJ kg^{-1} and the density of methane of 0.714 kg m^{-3} at STP (Equation 4-5). The actual methane slip was assessed as less than 1% from biogas upgrading, as the model incorporated off gas recirculation for further scrubbing and regenerative thermal oxidisation to treat the residual methane in the final off-gas. The electrical demand (ED_{UP}) and thermal demand (TD_{UP}) were calculated in kWh a^{-1} based on the amount of biogas upgraded (V_{AD}, m^3 a^{-1}). Detailed calculations of the electrical and thermal demands are summarised in the Appendix B.6.

Equation 4-5 Gross energy output of the upgrading process.

$$EO_{UP}\left(\frac{\text{kWh}}{\text{a}}\right) = \left[\left(V_{AD}\,(1 - CH_4Slip_{UP})\right) * cv_{CH_4}\right]/3.6$$

The final configuration considers biomethane production with the addition of a CHP unit fuelled by biogas that will provide electricity ($EO_{CHP-UPG}$, kWh a^{-1}) to cover the electrical demand of both the AD plant and the upgrading process (ED_{AD}, ED_{UP}, kWh a^{-1}). Based on the required electrical power for the anaerobic digestion process and biogas upgrading, a maximum CHP unit size of 18 kW_{el} was considered for the scenarios. In comparison to the upgrading configuration, this scenario uses a portion of the biogas produced to displace the use of fossil fuels in meeting the electric and thermal demand of the system. As such it produces less product in the form of biomethane (and hence lowers the revenue generated) but should also reduce the carbon footprint of the upgrading configuration by eliminating fossil use. It is assumed that the heat output ($HO_{CHP-UPG}$, MJ a^{-1}) generated by the CHP will be used to cover the thermal demand of the AD process (TD_{AD}, MJ a^{-1}) and, if the upgrading technology requires it, the upgrading thermal demand (TD_{UP}, MJ a^{-1}). If the heat output generated by the CHP unit is not enough to cover both thermal demands, it was considered that a boiler unit ($HO_{Boiler-UPG}$, MJ a^{-1}) would produce the remaining heat demand for the upgrading process and the AD process.

To calculate the volume of biogas that will be upgraded (V_{UPG}, m^3 a^{-1}) from the total biogas production (V_{AD}, m^3 a^{-1}), the required volume of biogas for the CHP unit (V_{CHP}, m^3/a) and boiler unit (V_{Boiler}, m^3 a^{-1}) (if required) was determined through a recursive quantitative process. Figure 4-3 provides the iterative procedure to calculate the volume of biogas required as the volume of biogas upgraded depends on the electric demand of both the AD process and the upgrading system (ED_{AD}, ED_{UP}, kWh/a).

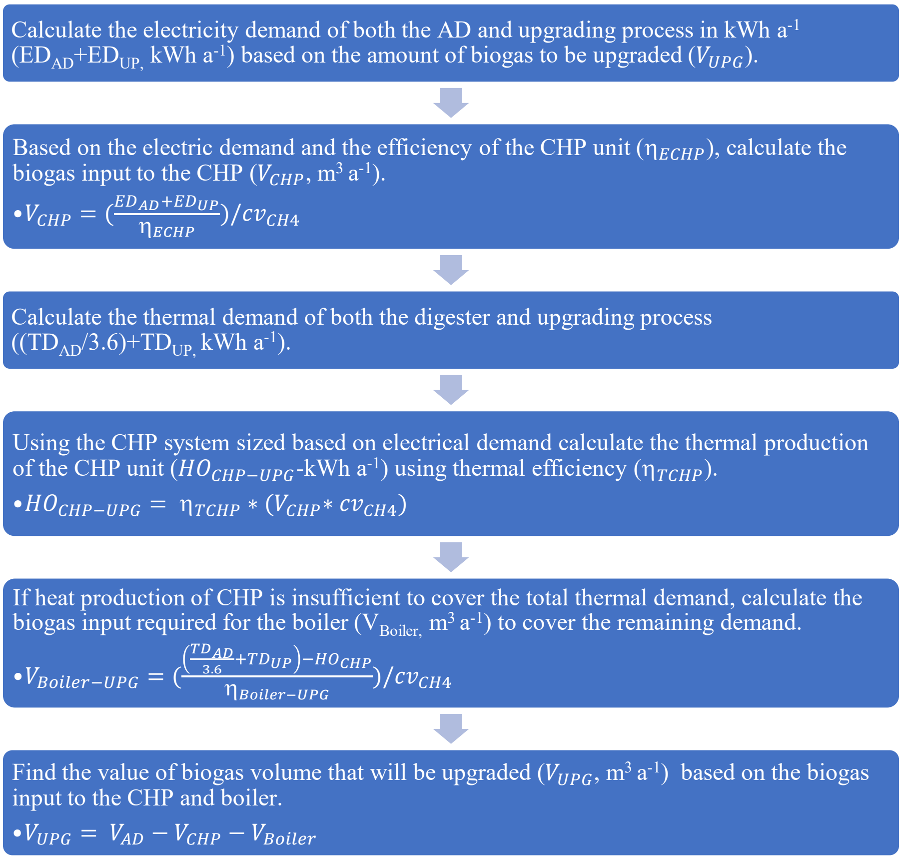

Figure 4-3 Flowchart of the iterative process to calculate the volume of biogas upgraded in the Upgrading + CHP configuration (see full details in Section B3 and Section B6 of Appendix B)

4.2.4 Economic Analysis

For this study, the capital cost (CAPEX) was set as direct fixed capital based on the cost of previous co-digestion systems of slurry and grass silage as shown in Appendix B.7 (Table B-6). For the boiler configuration a specific CAPEX of 72 € $t_{feedstock}^{-1}$ a^{-1} was used. For the CHP configuration a specific CAPEX of 107 € $t_{feedstock}^{-1}$ a^{-1} was used. The upgrading configuration (UPG) considered a specific CAPEX of 159 € $t_{feedstock}^{-1}$ a^{-1}, and the upgrading + CHP (UPG+CHP) configuration used a specific CAPEX of 183 € $t_{feedstock}^{-1}$ a^{-1}.

For each CAPEX, it is assumed that the cost for each configuration includes the required infrastructure, site works, and grid connection cost required to operate. Although, based on the region of analysis, additional costs may need to be included such as contingency costs, development costs, and engineering costs. For the CAPEX, a loan was considered to cover the initial cost of each of the AD systems based on common economic parameters for Ireland (Table 4-3).

Table 4-3 Economic Parameters for a loan considered to cover the capital cost of the AD systems.

Parameters	Value	Note
Debt ratio*	50%	Assumed
Interest on debt	2%	(40)
Loan period	10 years	Assumed
Inflation	2%	Increment applied to both OPEX and revenues. (41)

* The debt ratio is a ratio of the total debt to the total assets (CAPEX)

For the operational costs (OPEX), the cost was divided into fixed costs and variable costs. The fixed cost included the labour required to run the plant, maintenance, insurance, and administrative costs for the management of the facility. The labour cost was based on the individual salary of each worker and the operating hours of the system. For the scenarios assessed the labour cost was assumed to be 15 € hr^{-1}, which would be the typical rate for such labour in Ireland (37). The labour intensity was set to be 1 hr day^{-1} for the AD system and to be 2 hrs day^{-1} for the upgrading system based on systems with a similar capacity (42). For the maintenance, insurance, and administrative costs of the system, the values were based on a percentage of the CAPEX of the system as shown in Table 4-4.

Table 4-4 AD system operating cost for the different biogas end-use configurations.

Parameters	Value
Equipment maintenance	3% of the direct fixed capital (43)
Insurance	0.7% of the direct fixed capital (43)
Administrative Cost	1% of the operating labour

The variable cost was calculated based on the total feedstock acquisition cost, the annual electricity expense of the system, and the annual fuel expense based on the thermal and electrical demand of the system. For the scenarios analysed, in calculating the feedstock acquisition cost, the slurry cost was assumed to be 0 € t_{wwt}^{-1} as it is produced on the farm, while the grass silage price was set at 43 € t_{wwt}^{-1} based on the average silage cost for Ireland in 2022 (44). Detailed calculations of the variable costs are summarised in the Appendix B.8.

In assessing the economic benefits of a system, different revenue streams based on the four biogas end-use configurations were considered for each scenario as outlined in section 4.2.3. Revenue could be generated through tariffs, selling biomethane via the natural gas grid to customers for use as a transport fuel or for heat, avoidance of costs associated with synthetic fertiliser use by spreading digestate as a biofertiliser, and through the sale of heat for local use or in district heating. For the revenues, an income tax of 12.5% was used based on the corporation tax used in Ireland (43,45).

The tariff revenue for each configuration was assumed to be the annual heat output (HO_{CHP}, HO_{Boiler}, kWh a^{-1}) and electricity output (EO_{CHP}, kWh a^{-1}) for the respective configuration multiplied by the respective tariff for 15 years. The tariff for heat was based in the support scheme for renewable heat (SSRH) which accounts for 29.5 € MWh^{-1} (46). While for the generation of electricity, the tariff of 74.08 € MWh^{-1} from the renewable electricity support scheme (RESS) was considered (47). For the scenarios that used the boiler configuration, it was also assumed that heat would be used locally or sold through district heating (if available) based on a customer price of heat of 60 € MWh^{-1} (33). The revenue from the sale of biomethane was set at 53.7 €/MWh based on the weighted average price of the second half of 2022 for natural gas in Ireland for business consumers (48).

It was assumed that digestate will be spread on the farm as biofertiliser displacing synthetic fertiliser. Based on this assumption, the revenue was calculated based on the amount of nitrogen contained in the synthetic fertiliser that is displaced from the nitrogen requirements of the farm considering a value of 2.7 € kg N^{-1} (44). Detailed calculations of the displacement of synthetic fertiliser can be found in in the Appendix B.9.

The economic analysis carried out in the TEA includes the calculation of the NPV, IRR, and payback period for each scenario based on the specific configuration for the end-use of the biogas (boiler, CHP, biogas upgrading, biogas upgrading + CHP). Once all the possible sources of incoming and outgoing cash flow for the farm were determined, the NPV was calculated as shown in Equation 4-6.

Equation 4-6 Net Present Value calculation.

$$NPV(€) = \sum_{t=0}^{L} \frac{(R_t - C_t)}{(1+r)^t}$$

Where C_t represent the cost incurred in year t, this includes the (CAPEX, OPEX, and income tax incurred), R_t are the revenues obtained in year t, L is the lifetime of the selected system in years and r represents the discount rate of the plant. A discount rate of 10% was used as recommended for renewable energy investments (49), and a system lifetime of 15 years was assessed.

The IRR and Payback Period were also calculated based on the discount rate and lifetime of the system selected. The discount rate at which the value of the NPV was equal to zero was considered in establishing the IRR (Equation 4-7). The payback period was the year "t" in which the cash flow compensated the initial investment. The discounted payback period was also calculated considering the value of money over time based on the discounted cash flow.

Equation 4-7 Internal Rate of Return.

$$NPV(€) = \sum_{t=0}^{L} \frac{(R_t - C_t)}{(1+IRR)^t} = 0$$

4.2.5 Environmental Calculation and abatement cost assessment

To calculate the net GHG emissions (kg CO_{2eq} a^{-1}) for each scenario the system boundary recommended by the RED-II methodology, including emissions savings from displaced use of synthetic fertiliser and emissions from energy displaced, was used as shown in Equation 4-8 (19).

Equation 4-8 Emissions considered for the analysis based on the REDII methodology to assess GHG emissions.

$$GHG_{conf,n} = \sum_{1}^{n} S_n \times \left(e_{ec,n} + e_{td,feedstock,n} + e_{l,n} - e_{sca,n}\right) + e_p + e_{td,product} + e_u - e_{ccs} - e_{ccr} - e_{fd} - e_{ed}$$

Where S_n accounts for the energy share of each feedstock n used (grass silage and slurry) to produce the biofuel (biogas or biomethane), $e_{ec,n}$ are the emissions associated with the cultivation of feedstock; $e_{td,feedstock,n}$ is the emissions from the transport of the feedstock to the digester; $e_{l,n}$ are the emissions from carbon stock changes caused by land-use changes for feedstock n; e_p is the emissions from processing the feedstocks (arising from the AD process and upgrading process which includes methane leaks and methane slip). For biogas upgrading the initial off gas was considered to have 6% methane composition based on small-scale water scrubbing. However, the model incorporated off gas recirculation for further scrubbing and regenerative thermal oxidisation to treat the residual methane in the final off-gas. This reduces the methane concentration in the off-gas by 99.5% which results in a total of 0.03% of methane in the off-gas at the end of the upgrading process (50). $e_{td,product}$ are the emissions from the transport of biogas or/biomethane and e_u is the emissions from fuel in use. The emissions savings are accounted by $e_{sca,n}$ from improved agricultural management of feedstock (-54 $kgCO_{2eq}\ t_{wwt}^{-1}$), e_{ccs} are the emissions savings from CO_2 capture and geological storage and e_{ccr} from CO_2 capture and replacement of fossil fuels (both e_{css} and e_{ccr} were assumed to be zero), e_{fd} are the emissions savings from the displacement of synthetic fertiliser use and e_{ed} the emissions savings from energy displacement. This considers that heat and electricity produced by the CHP and Boiler configuration will displace energy from fossil fuel origin and that biomethane will be use as transport fuel displacing diesel.

The share of energy (S_n) of each feedstock n was calculated as a fraction of input into the digester using the following two equations:

Equation 4-9 Share of energy of feedstock n in energy content.

$$S_n = \frac{P_n * W_n}{\sum_1^n P_n * W_n}$$

Equation 4-10 Weighting factor of feedstock n.

$$W_n = \frac{I_n}{\sum_1^n I_n}$$

The weighting factor (W_n) was calculated based on the annual input (I_n) to the digester of each feedstock n ($t_{wwt}\ a^{-1}$) divided by the total amount of input of feedstock to the digester (Equation 4-10). While in Equation 4-9, P_n represent the biogas energy yield in MJ kg^{-1} provided by each feedstock n in the production of the biofuel. Further details on the calculation of the GHG assessment for each of the emissions generated by each feedstock are detailed in the Appendix B.10.

To evaluate the cost of GHG abatement and the abatement potential, the abatement cost was calculated for each scenario based on the IPCC methodology (51). The abatement costs were calculated based on the NPV and the total discounted GHG emissions (DGE) generated by each different configuration (Equation 4-11). For each configuration, the discounted abatement cost (DAC) was calculated in € per tCO_{2eq} by multiplying the undiscounted GHG emissions of each different configuration ($GHG_{conf,n}$- tCO_{2eq}) by an annuity factor or discount factor (DF) to convert the emissions to the present value (Equation 4-12). Finally, the NPV (€) is divided by the discounted emissions (DGE - tCO_{2eq}) to obtain the discounted abatement cost.

Equation 4-11 Discounted abatement cost calculation.

$$DAC\left(\frac{€}{t\ CO_{2eq}}\right) = \frac{-NPV}{DGE}$$

Equation 4-12 Discounted GHG emissions calculation.

$$DGE\ (t\ CO_{2eq}) = GHG_{conf,n} \times DF$$

To calculate the discount factor (%) (Equation 4-13), an environmental discount rate of 4% (r) was used based on the Irish code for emissions appraisals taking into account the lifetime of the system (L) detailed in section 4.2.4 (52).

Equation 4-13 Discounted factor to convert future value to present value.

$$DF = \frac{((1+r)^L - 1)}{(r * (1+r)^L)}$$

4.3 Results and Discussion

4.3.1 Economic analysis results

The NPV, IRR and payback period were calculated for each of the different hypothetical farms (with herd sizes of 40, 60, 100 and 185) considering the 4 biogas end-use configurations (Boiler, CHP, Upgrading, and Upgrading + CHP). The results are shown in Table 4-5. Most of the farms assessed had a negative NPV which implied that they were not financially viable. The system that performed the best economically was the boiler configuration which had three sources of revenue: the renewable heat incentive, the sale of exported heat and the avoided synthetic fertiliser costs, and furthermore this system had the lowest capital cost. The boiler configuration for a herd size of 185 proved to be the only financially viable system that obtained a positive NPV with a payback period of 6 years and a discounted payback period of 11 years. Furthermore, this scenario had an IRR of 13% suggesting it was a good financial investment decision based on a discount rate of 10%. This scenario had a net heat output of 1,572 MWh a^{-1}. Installation of such a system could cover the thermal demand for small areas with low heat demand of ca. 1,000 MWh km^{-1} (32).

Table 4-5 Results from the economic analysis for 16 scenarios. k€ represents thousands of euros.

Configuration/Scenario	CAPEX (k€)	NPV (k€)	Heat Produced (kWh a^{-1})	Electricity Produced (kWh a^{-1})	Biomethane Production (m^3 a^{-1})
Boiler 40	€45.12	-€38.49	281,293	-	-
Boiler 60	€76.69	-€26.26	512,986	-	-
Boiler 100	€124.15	-€18.74	823,093	-	-
Boiler 185	€233.88	€21.70	1,572,464	-	-
CHP 40	€66.96	-€85.88	159,604	100,983	-
CHP 60	€113.80	-€108.34	290,360	177,483	-
CHP 100	€184.23	-€147.04	467,264	283,457	-
CHP 185	€347.05	-€230.18	896,754	538,539	-
UPG 40	€99.44	-€332.03	-	-	34,002
UPG 60	€169.01	-€476.89	-	-	61,283
UPG 100	€273.60	-€685.65	-	-	97,950
UPG 185	€515.41	-€1,172.63	-	-	186,004
UPG+CHP 40	€114.36	-€296.33	48,703	28,098	24,849
UPG+CHP 60	€194.36	-€415.31	86,945	50,161	44,943
UPG+CHP 100	€314.63	-€589.92	139,250	80,336	71,781
UPG+CHP 185	€592.72	-€996.84	140,603	152,362	136,374

Figure 4-4 and Figure 4-5 show the associated operating costs and revenues for each of the 16 scenarios based on the biogas end-use configuration used and by herd size (40, 60, 100, 185). For all scenarios, the high operating cost meant that most of the systems were not economically feasible. The main source of expense for the scenarios arose from the feedstock. Grass silage represented between 64% to 79% of the cost in scenarios with the boiler and CHP configurations and 34% to 66% for the scenarios that considered biogas upgrading (UPG and UPG+CHP). In a previous study it was found that approximately half of the total cost of methane production was associated with the acquisition of grass silage as feedstock for an AD facility (53). This high price for grass silage comes from an unprecedented increase in the price of fertilisers and fuel due to recent geo-political events between 2021 and 2022 (44).

Furthermore, the scenarios with upgrading had two additional sources of high operating costs arising from labour (8% to 40%) and electricity purchase (18% to 24%). In particular, labour represented a high operating cost for smaller systems as the hours required to operate the system were considered to be the same for all scenarios. Furthermore, for biogas upgrading via water scrubbing, the electrical energy consumption was quite high at 0.45 kWh m^{-3} biogas as the main system components (compressor, water pump and cooling) have relatively high energy demands in small-scale systems (39). This may be challenging in the short term with Irish electricity prices expected to increase by 19% for the last quarter of 2022 due to recent geo-political events (54). The scenarios UPG+CHP were more attractive than the UPG scenarios as the operational cost was reduced between 21% to 28% with only a 15% increase in the total capital cost from the acquisition of the CHP unit and boiler unit (if needed).

For the boiler and CHP configuration, one of the main revenue streams considered in this analysis are the tariffs offered through the support scheme for renewable heat (SSRH) and the renewable electricity support scheme (RESS). Although when compared to the operational cost of the systems it would only cover 32% to 40% of the total operational cost for the boiler configuration and 47% to 58% for the CHP configuration. This would pose a problem in areas where there is insufficient heating demand to consider the sale of exported heat through district heating, as this income represents 62% of the total income for the boiler configuration and 41% for the CHP configuration of the scenarios assessed. To be suitable for district heating, the on-farm AD system would need to be in proximity to dense urban areas or large industries with sufficient heat demand that requires shorter pipelines, which would make them attractive to investors (33). With the Irish government introducing an obligation for the heat sector to increase the use of renewables by 2024, district heating could provide a potential investment opportunity (55). The latest *Climate Action Plan* recommends that the installed capacity of district heating in Ireland should be 0.8 TWh by 2025 and increase to 2.7 TWh by 2030 (56). Furthermore, Irish farms in general lack the thermal demand to use all of the potential heat generated from the biogas produced, although an alternative would be to sell the biogas to a large industrial energy user in proximity to the farm that had sufficient heat demand and was interested in reducing its carbon footprint (57). Furthermore, a higher support tariff may be required for developers to procure positive NPVs and lower payback periods. Prior studies have indicated that higher incentives to produce biomethane may be required for the development of AD systems in rural decentralised areas as compared to urban areas due the higher production costs of biomethane (45).

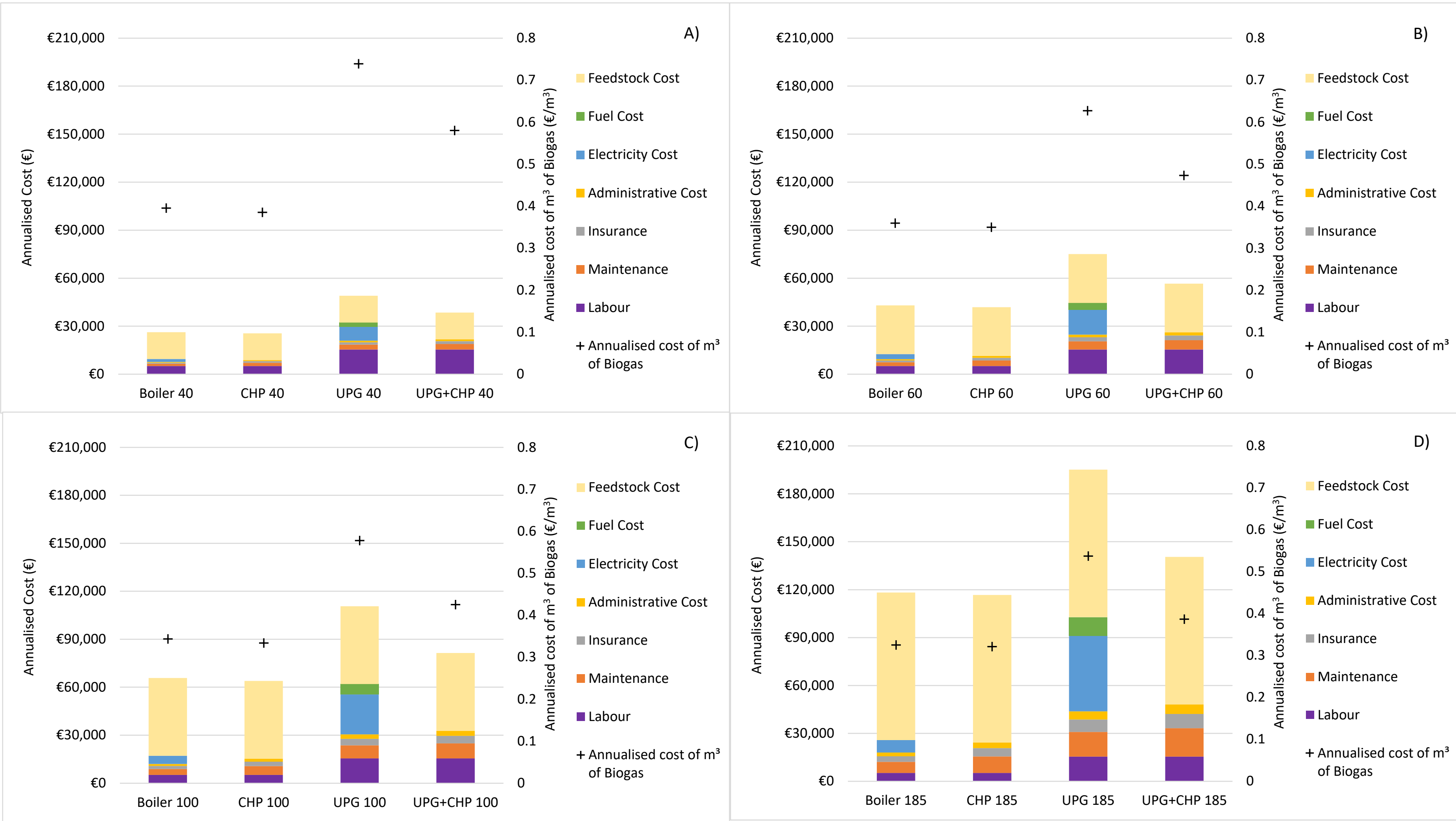

Figure 4-4 Total annual operating cost and annualised cost of m³ of biogas (Gross Production) for each of the 4 different biogas end-use configurations (boiler, CHP, upgrading, upgrading + CHP), based on the assessed systems for on-farm AD for herd size of A) 40, B) 60, C)100 and D)185 dairy cows.

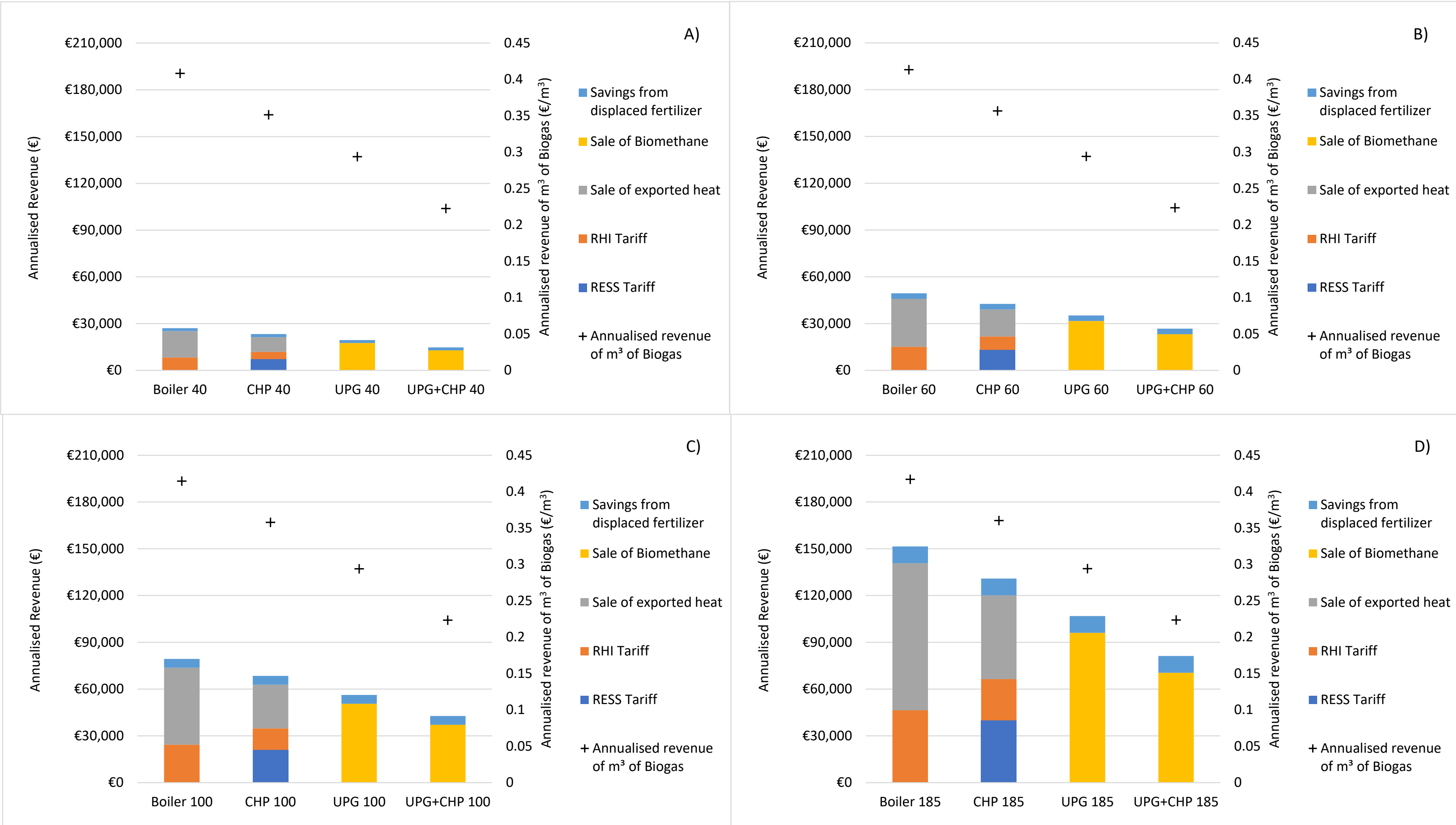

Figure 4-5 Total annual revenues and annualised revenues of m³ of biogas (Gross Production) for each of the 4 different biogas end-use configurations (boiler, CHP, upgrading, upgrading + CHP), based on the assessed systems for on-farm AD for herd size of A) 40, B) 60, C)100 and D)185 dairy cows.

For the scenarios that included biogas upgrading (UPG and UPG+CHP), the two sources of income considered were the sale of biomethane and the displaced synthetic fertiliser costs. However, revenues did not compare favourably to the operational cost of these configurations; it only covered 56% to 59% of the operating cost (scenarios UPG and UPG+CHP). Furthermore, small-scale upgrading systems have high investment costs since elements of the equipment such as the valves, analysis equipment and pipes used for smaller systems are the same as that required for larger capacity systems (39), thus, the financial viability of the system is reduced as the revenues generated are not enough to pay for the initial capital investment. In the case of the UPG+CHP system the revenue was reduced as part of the biogas was used to cover the electric and thermal demand of the process and there was an additional capital cost by integrating a small CHP unit (as the boiler was not required for water scrubbing).

Consideration of additional sources of revenue, such as increasing the selling price of biomethane, or the addition of financial supports, could make such systems more economically viable. Previous TEAs of small-scale anaerobic digestion systems that have digested manure/slurries have acknowledged similar profitability in both developing countries such as India (58), Nigeria (59) and Bolivia (60), and in developed countries such as UK (61), Turkey (62) and Spain (63). Furthermore, in a more advanced operation, the solid fraction of digestate could be converted into high-value by-products such as biochar, bio-oil and syngas through pyrolysis (64), while the liquid fraction could be used as a culture medium for microalgae cultivation which in turn can be used to generate valuable chemicals or proteins (65–68). However, both options would require a significant investment for small-scale systems considering the additional equipment required. Another source of income could be generated from the CO_2 by-product of the upgrading process which could be separated and sold for use in the food industry (69). Although considering these options might increase the capital and operating costs of the systems further analysis would be required to assess if the income generated would be sufficient to cover these costs and make a profit.

4.3.2 Environmental analysis results

In conducting the environmental analysis, the net GHG emissions for all of the scenarios (considering the biogas end-use configurations for each hypothetical farm size) were calculated based on the boundary set by the Recast RED-II methodology with the inclusion of savings from energy displacement (heat, electricity and transport fuel) and displacement of synthetic fertiliser (19). Figure 4-6 shows the GHG emissions of the 16 scenarios.

The largest source of emissions for all the scenarios came from the methane leakage that includes for leakage during biogas production and the methane slip during the upgrading process. For all scenarios this represented between 43% to 46% of the total emissions generated. The second and third largest source of emissions came from grass cultivation which includes the direct emissions from fertiliser use and the direct and indirect nitrous oxide (N_2O) emissions from fertiliser application. Fertiliser emissions ranged between 24% to 28% of the total emissions for the boiler, CHP and UPG+CHP configuration while for the upgrading configuration it represented between 12% and 13% of the emissions. For the upgrading scenarios the biogas production and the upgrading process generated higher emissions than the other configurations as the energy required for the AD process and upgrading process was provided from the electricity grid and the gas grid. For the scenarios with CHP configurations, there were no emissions associated with the biogas production as the energy required for the AD process (electric and thermal demand) was provided by the CHP unit. In the UPG+CHP scenario, integrating the CHP unit reduced emissions and increased the sustainability of the system as compared to the UPG scenario since there were no fossil fuels associated with biogas production or biomethane upgrading.

The emissions from grass cultivation result primarily from the amount of synthetic fertiliser required to meet the nitrogen demand for the farm after using the digestate as a biofertiliser. However, the amount of synthetic fertiliser could be reduced close to zero with the inclusion of white clover while cultivating perennial ryegrass species in multi-species grass swards as the nitrogen fixed by the white clover can cover the remaining nitrogen requirement (up to 120-150 kgN ha^{-1}) of the grass (44). One significant contributor of emissions in biogas production and upgrading is the methane leakage and slip which has a significant impact on the emissions balance and is dependent on the type of anaerobic digestion system and the specific upgrading technology used in the process (70). Water scrubbing- based plants in general can have higher methane slip in comparison to amine-based and membrane-based technologies thus higher GHG emissions are evident from water scrubbing (50). Furthermore, based on the type of upgrading process, there can be an increase in emissions based on the electricity consumption of the system if compressing, pumping and storage systems are required (70).

Most of the scenarios evaluated achieved high emissions savings through the displacement of energy (heat, electricity, and transport fuel); specifically, 70% emissions savings for the boiler and CHP configurations and 75% and 69% of the savings for the upgrading and upgrading + CHP configurations, respectively. These emissions could reduce in the future as renewable energy will reduce the emissions associated with the use of fossil fuels in electricity generation and the need to import natural gas. In terms of transport fuels, the emissions from natural gas combustion fuel offer 25% fewer CO_2 emissions than diesel-fuelled trucks (71). The inclusion of slurry as a feedstock for AD allows for the capture of methane that may have been released into the atmosphere from open slurry holding tanks; thus, the AD plant could be considered a carbon-negative technology (on a whole life cycle basis) and further increase the overall GHG emissions savings over the full life cycle (71). However, in the case of co-digestion of different substrates to produce biogas or biomethane the RED methodology only accounts for the emissions savings of each feedstock based on the share of feedstock in the energy content. Based on the feedstock mixture, slurry only provides 5% of the total energy content for the analysis which reduced the potential savings from slurry management to only 5% of the total emissions savings from treating the slurry (-54 kg CO_{2eq} tFW^{-1} manure) which may be considered conservative with the current methodology. The detailed results of the environmental and economic analysis can be found in the Appendix B sections B11 and B12.

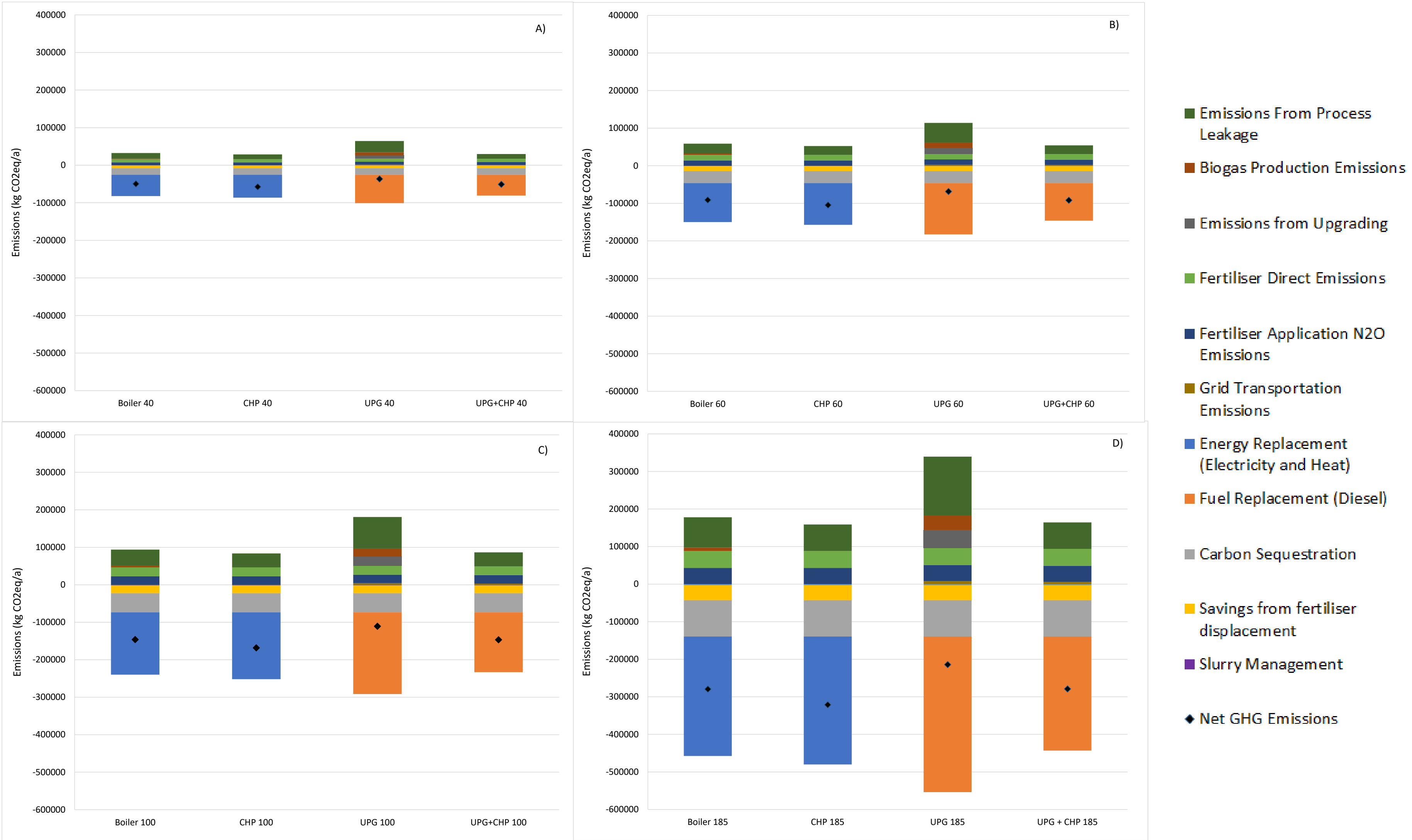

Figure 4-6 Emissions saved and generated in the 4 different biogas end-use configurations (boiler, CHP, upgrading, upgrading + CHP), based on the assessed systems for on-farm AD for herd size of A) 40, B) 60, C)100 and D)185 dairy cows.

4.3.3 Levelised abatement cost analysis results

The results of the TEA and GHG assessment allow for the evaluation of the abatement costs for each scenario as shown in Table 4-6. This includes the undiscounted and discounted emissions using a discount rate of 4% in guidance with the Irish Public Spending Code (52). The discounted abatement costs of the systems varied from -7 € tCO_{2eq}^{-1} to 816 € tCO_{2eq}^{-1} for the 16 scenarios evaluated. Each scenario considered different system boundaries comprising of varying revenue streams, costs, and emissions. It is evident from the results that the scale of the plant has a significant impact on the associated abatement cost as the costs decrease based on economies of scale. These results illustrate that the abatement cost and potential of individual AD plants are variable, and a single value may not accurately represent the potential mitigation achievable by the technology. The scenarios that provided the highest mitigation potential were the ones that considered the boiler and CHP configurations as the abatement cost values were below the carbon tax set for Ireland for 2030 of 80 €/tCO2 except for the CHP 40 and 60 scenarios (72). The scenarios with biogas upgrading had relatively high abatement costs as shown in Figure 4-7. This can be explained by the lack of sufficient subsidies or incentives and the high capital cost as indicated in section 4.3.1. Opportunities to increase the feasibility of these systems would include increasing the biomethane selling price to improve the financial performance, or community cooperative approaches in which farms would transport their biogas to a centralised upgrading facility and overcome the high costs associated with small-scale biogas upgrading flow rates (73).

Table 4-6 Assessment of abatement cost of different configurations for biogas end-use (boiler, CHP, upgrading, upgrading + CHP) and varying dairy herd size.

Configuration/ Scenario	Annual GHG abatement ($tCO_{2eq}\ a^{-1}$)	NPV for lifetime of the project (€)	Total GHG Mitigation (tCO_{2eq})	Abatement Cost (€ tCO_{2eq}^{-1})	Discounted GHG Mitigation (tCO_{2eq})	Discounted Abatement cost (€ tCO_{2eq}^{-1})
Boiler 40	50	-€38,490	747	52	553	70
Boiler 60	91	-€26,261	1366	19	1013	26
Boiler 100	146	-€18,739	2192	9	1625	12
Boiler 185	280	€21,703	4193	-5	3108	-7
CHP 40	58	-€85,881	863	100	640	134
CHP 60	105	-€108,335	1573	69	1166	93
CHP 100	168	-€147,037	2524	58	1871	79
CHP 185	321	-€230,183	4821	48	3573	64
UPG 40	37	-€332,032	549	605	407	816
UPG 60	69	-€476,889	1028	464	762	626
UPG 100	111	-€685,647	1662	413	1232	557
UPG 185	214	-€1,172,633	3214	365	2383	492
UPG+CHP 40	51	-€296,334	764	388	566	523
UPG+CHP 60	92	-€415,306	1379	301	1022	406
UPG+CHP 100	147	-€589,917	2203	268	1633	361
UPG+CHP 185	279	-€996,842	4184	238	3102	321

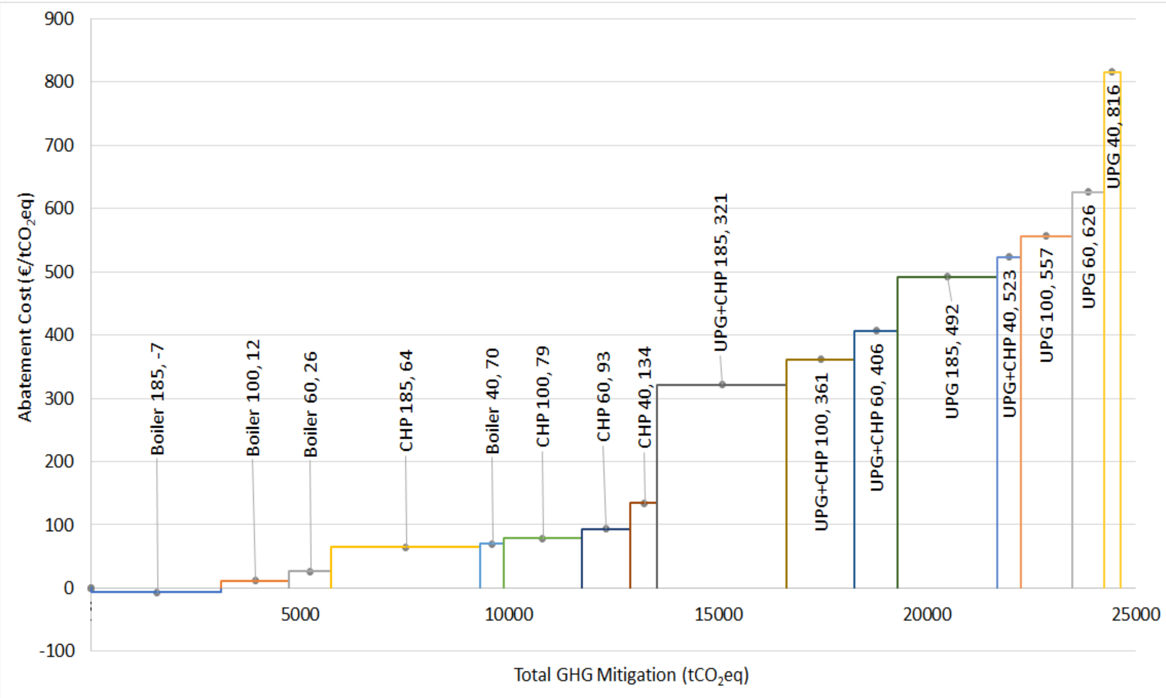

Figure 4-7 Discounted abatement cost curve for on-farm AD systems.

4.3.4 Input variable change and the effect on abatement cost

To fully understand the barriers that need to be addressed in making on-farm AD systems financially viable while representing the abatement potential of the system it is important to take into consideration how alterations to input cost, revenues, technologies, fuels, and emissions boundary can directly alter the abatement cost. An example of this would be to consider changes to single variables such as:

- Cost of feedstock (change input cost – IC),
- Increase in tariff or sale prices (change input revenue – IR),
- Different biogas upgrading technology such as membrane upgrading (change input technology – IT),
- Different energy input source for the boiler used in AD and the upgrading process such as oil or woodchips (change in fuel – F_{OIL}, F_{WOOD})
- System boundary used by the RED II methodology that excludes emissions savings from displaced use of synthetic fertiliser and energy displaced (SBE).

Based on these input changes, amendments were made for the 4 different biogas end-use configurations (Boiler, CHP, UPG and UPG+CHP) for a dairy herd of 185 to evaluate the effect of an input variable change. The amended abatement results are shown in Table 4-7. For the change in feedstock cost (IC), it was considered that there were no associated costs acquiring the feedstock. This can be considered akin to using food waste or slaughterhouse waste as a feedstock substitute for grass silage. Furthermore, no additional costs were considered in terms of CAPEX as the purpose was to evaluate the change in a single variable.

For the change in revenue (IR), an increase in incentives for the boiler and CHP configuration was considered while an increase in the biomethane sale price was considered for the upgrading configurations (UPG, UPG+CHP). For the boiler configuration an increase of 50% (36.88 € MWh^{-1}) in the support scheme for renewable heat (SSRH) was considered and for the CHP configuration an increase in the RESS tariff was applied using the reference price of the past REFIT tariff for 2022 of 164.31 € MWh^{-1} (74). This takes into consideration the increase in the cost of fuels due to recent geo-political events. Natural Gas commercial price had a percentage change between 21.8% to 74.4% while electricity also increased between 4.9% to 54.9% across all consumption bands from 2021 to 2022 (48). This increase also was applied to the biomethane selling price; a selling price of 160 € MWh^{-1} was modelled due price volatility, similar to the current natural gas prices in Denmark (74).

To reflect a change of technology (IT), considering a different upgrading method such as membrane separation could increase biomethane production based on the increased methane recovery and reduced electrical demand. More significantly, the methane in the off-gas due to methane slip is reduced from 6% in water scrubbing to 0.105% in membrane separation. To cover the thermal demand, oil (F_{OIL}) and wood (F_{WOOD}) were evaluated instead of natural gas to cover the thermal demand of the process to compare the impact on mitigation and financial performance. Finally, to assess a different system boundary for the emissions (SBE), the system boundary recommended by the RED-II methodology was assessed, this boundary excludes the emissions savings from the displaced use of synthetic fertiliser and emissions saved from energy displacement (heat, electricity, and transport fuel).

4.3.5 Results of input change to abatement costs

As per Table 4-7, the abatement costs were amended based on the new assumptions and varied significantly for the different scenarios. This is further indicated in the amended abatement cost curve displayed in Figure 4-8 which is based on alterations to the input variables. In the scenarios with no associated cost acquiring feedstock (IC), the abatement cost varied between -227 € tCO_{2eq}^{-1} to 72 € tCO_{2eq}^{-1} for the four biogas configurations with a 185-herd size, significantly lower than the previous assessment (Table 4-6) in which the same scenarios ranged between -7 € tCO_{2eq}^{-1} to 492 € tCO_{2eq}^{-1}. By reducing a cost variable in the analysis, the scenarios for both boiler and CHP increased their potential profits making them a financially viable mitigation option, whilst the upgrading + CHP configuration reached a cost below the carbon tax set for Ireland for 2030 of 80 € tCO_2^{-1} (72).

When an increase in the input revenue (IR) was incorporated, all scenarios became financially viable obtaining an abatement cost from -32 € tCO_{2eq}^{-1} to -148 € tCO_{2eq}^{-1} making the technology more attractive to investors compared to the original results in Table 4-6. Based on these results the cost and revenues pose one of the main barriers to integrate anaerobic digestion to farms. An additional analysis looking at a range of fiscal incentives could be also analysed to allow Ireland to decarbonise the agriculture sector at minimal cost to the taxpayer. This may be prudent considering that Ireland will increase the production of biomethane from anaerobic digestion to 1 TWh by and to 5.7 TWh by 2030 (56).

Using a different upgrading method (membrane separation) as a change on the input technology (IT) the abatement cost of the upgrading configurations decreased from 492 € tCO_{2eq}^{-1} and 321 € tCO_{2eq}^{-1} (for water scrubbing) to 338 € tCO_{2eq}^{-1} and 255 € tCO_{2eq}^{-1} for the upgrading and upgrading + CHP configuration by increasing the GHG mitigation potential due the reduced emissions in terms of methane slippage and higher biomethane production due the increased methane recovery.

Using oil (F_{OIL}) and wood (F_{WOOD}) as fuels to produce heat also altered the abatement cost and abatement potential. Oil has a higher associated cost and emissions factor than natural gas, thus the abatement cost increased for the upgrading configuration from 492€ tCO_{2eq}^{-1} to 598 € tCO_{2eq}^{-1}. Woodchips also had a higher cost than natural gas, but as it is considered a zero-emissions fuel the annual abatement was higher at 271 tCO_{2eq} a^{-1} compared to 194 tCO_{2eq} a^{-1} using natural gas with a total abatement cost of 570 € tCO_{2eq}^{-1}.

Table 4-7 Assessment of input changes to the abatement cost of different configurations for biogas end-use (boiler, CHP, upgrading, upgrading + CHP) changing input variables of the analysis. The input changes include change to input cost (IC), input revenue (IR), input technology for the upgrading configurations (IT) and change of system boundary for GHG assessment (SBE).

Configuration/ Scenario / Input Change	NPV for lifetime of the project (€)	Discounted GHG Mitigation (tCO_{2eq})	Discounted Abatement cost (€ tCO_{2eq}^{-1})
Boiler 185-IC	€706,908	3108	-227
CHP 185-IC	€462,104	3573	-129
UPG 185-IC	-€389,997	2383	164
UPG+CHP 185-IC	-€224,077	3102	72
Boiler 185-IR	€98,936	3108	-32
CHP 185-IR	€144,342	3573	-40
UPG 185-IR	€351,732	2383	-148
UPG+CHP 185-IR	€124,497	3102	-40
UPG 185-IT	-€1,019,264	3012	338
UPG+CHP 185-IT	-€912,218	3579	255
UPG 185-FOIL	-€1,290,522	2159	598
UPG 185-FWOOD	-€1,719,242	3015	570
Boiler 185-SBE*	€21,703	-427	NA
CHP 185-SBE*	-€230,183	-214	NA
UPG 185-SBE*	-€1,172,633	-2222	NA
UPG+CHP 185-SBE*	-€996,842	-275	NA

Notes- IC = No feedstock cost; IR = change in revenue; IT = change in technology – membrane separation; SBE = change in system boundary – RED II.

Finally, excluding the scenarios that didn't consider emissions savings from the displaced use of synthetic fertiliser and emissions saved from energy displacement (SBE) (heat, electricity and transport fuel) an overall positive mitigation was achieved by all the configurations. The total abatement for SBE scenarios resulted in negatives values which meant the emissions savings were lower than the emissions generated during the process. In effect, only the emissions savings from the carbon sequestration of the grass (2.2 tCO_2 ha^{-1} a^{-1} (21)) and slurry management (-54 kgCO2eq t_{wwt}^{-1} (19)) can be taken into account based on the RED II methodology. Although the scenarios generated emissions using the RED II methodology (SBE), the boiler, CHP and UPG+CHP scenarios complied with the emissions savings required by the sustainability criteria (Table 4-8). The saving criteria set by RED-II (recast) requires 80% of GHG emissions savings against the fossil fuel comparator (FFC) for heat and electricity and 70% for transport. The FFC is set at 80 gCO_2 MJ^{-1} for heat, 183 gCO_2 MJ^{-1} for electricity and 94 gCO_2 MJ^{-1} for transport fuel (19). For the UPG scenario, the sustainability of the system is reduced as energy sourced from fossil fuels was considered to generate the electricity and heat used by the system. This analysis shows that a single change of variable or consideration within the system boundary for the emissions can have a notable influence on the abatement cost. Incorporating uncertainty analysis for such variables would allow for a more robust evaluation of scenarios.

Table 4-8 Renewable Energy Directive sustainability check for the scenarios of 185 cows of different configurations for biogas end-use (boiler, CHP, upgrading, upgrading + CHP).

Scenario	Total Emissions (g CO_2 MJ^{-1})	FFC (g CO_2 MJ^{-1})	Emissions Saved	Emission Savings Criteria	Criteria
Boiler 185-SBE	15.3	80	81%	80%	Sustainable for Heat
CHP 185-SBE	8.2 / 13.5	80 / 183	90% / 93%	80%	Sustainable for both Heat and Electricity
UPG 185-SBE	37.2	94	60%	70%	Not Sustainable for Transport
UPG+CHP 185-SBE	13.6	94	85%	70%	Sustainable for Transport

This potential uncertainty on the system performance can be coupled with the uncertainty of energy prices and fertiliser costs due to recent geo-political events which can directly affect the viability of the system. It is evident that a more detailed analysis is required for the cost, revenue, and emission variables that can directly affect the abatement cost. Further evidence could be gleaned from future research that integrates Monte Carlo simulation and uncertainty analysis to visualise the potential range of abatement potential and abatement cost that on-farm AD systems can achieve through a modified probabilistic abatement cost curve.

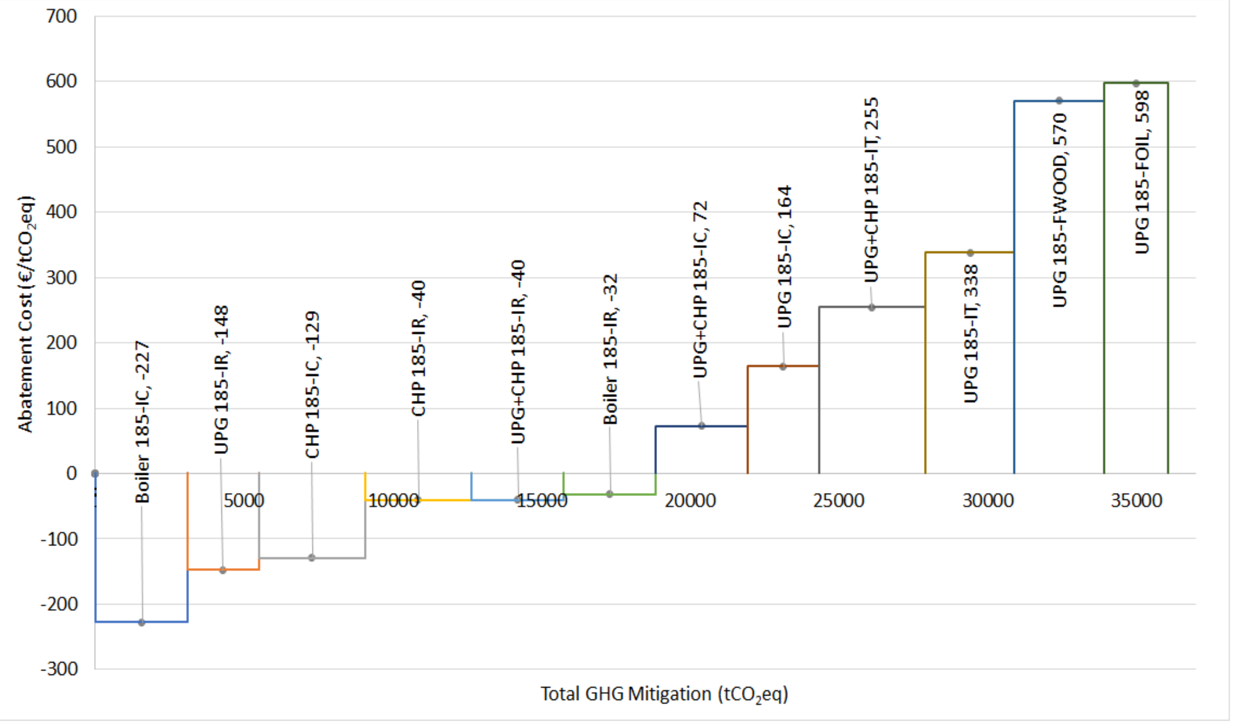

Figure 4-8 Abatement cost curve for on-farm AD systems. Different changes in variables were evaluated for the biogas end-use configurations for a herd size of 185 dairy cows.

4.4 Conclusion

Four objectives were set out in this paper and the key findings for each are presented below:

- Generate scenarios for on-farm AD that incorporate different configurations in terms of biogas end-use and varying farm size.

This work compared 16 different scenarios evaluating 4 different biogas end-uses (boiler, CHP, upgrading and upgrading +CHP) and 4 different farm sizes (40, 60, 100 and 185 dairy cow herds) where grass silage and cattle slurry were considered as feedstocks. These scenarios represented the average farm sizes and herd sizes in Ireland based on the latest data available.

- Calculate the key parameters of a TEA and the GHG emissions generated for the scenarios outlined.

In evaluating the 16 scenarios, it was evident that the majority of anaerobic digestion systems were not financially viable with current cost of feedstock and energy at these relatively small scales. The only scenario that proved to be viable was the boiler configuration for a herd size of 185 cows in which the heat produced was sold through district heating. The least economically feasible scenarios occurred when biogas upgrading was included due to high operational and capital costs. To make the current systems viable there is a need to increase the sources of revenues or consider higher financial supports for on-farm AD systems. This insight can guide policies to target the necessary incentives to enable the penetration and further development of the adoption of anaerobic digestion in Ireland. All systems obtained negative net GHG emissions considering savings from energy displaced sourced from fossils fuel and from the use of biofertiliser to displace the use of synthetic fertiliser.

- Calculate the abatement cost and the mitigation potential for each on-farm AD scenario.

The cost of mitigation for the different scenarios varied between -7 € tCO_{2eq}^{-1} to 816 € tCO_{2eq}^{-1}. The scenario that had the lowest abatement cost was the Boiler configuration with a herd size of 185, making it a potentially viable option for on-farm AD. This scenario considered that the heat produced would be sold in a district heating system or to a large energy user. The scenarios with the lowest viability were the upgrading scenarios since most of the farms were relatively small to incorporate such a large capital cost and operational cost. Furthermore, the net GHG mitigation was lower as energy sourced from fossil fuels was used to cover the heat and electricity demand of the system.

- Assess the implications of changing the input variables in the calculation of abatement cost and illustrate the effect of changing the AD system boundary in terms of emissions savings.

A single change in an input variable or a change in the system boundary for the calculation of the emissions can greatly alter the financial and environmental performance of such AD systems. For example, having no associated cost to acquire feedstock (considering that food waste and slaughterhouse wastes can substitute grass silage) altered the marginal abatement cost from -227 € tCO_{2eq}^{-1} to +72 € tCO_{2eq}^{-1} for the different biogas end-use configurations and a herd size of 185 (as compared to the abatement cost for the same scenarios with a feedstock cost included: -7 € tCO_{2eq}^{-1} to 492 € tCO_{2eq}^{-1}). If an increase in tariffs and biomethane sale prices is considered, the financial viability of the systems that considered upgrading improve by decreasing the marginal cost to between -148 € tCO_{2eq}^{-1} to -32 € tCO_{2eq}^{-1}, ultimately making the investment more attractive. This shows that a single value for the marginal abatement cost for on-farm AD may not be able to accurately capture the inherent variability of these systems. The use of sensitivity analysis would enable the identification of input variables that directly affect the marginal cost and abatement.

References

1. Giannakis E, Zittis G. Assessing the Economic Structure, Climate Change and Decarbonisation in Europe. Earth Systems and Environment [Internet]. 2021 Sep 1 [cited 2022 Apr 19];5(3):621–33. Available from: https://link.springer.com/article/10.1007/s41748-021-00232-7

2. Sustainable Food SI. Agriculture & Food in Ireland [Internet]. [cited 2022 Apr 19]. Available from: https://www.sfsi.ie/agriculture-food-ireland/

3. Agriculture | Environmental Protection Agency [Internet]. [cited 2022 Oct 26]. Available from: https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/agriculture/

4. Bose A, O'Shea R, Lin R, Long A, Rajendran K, Wall D, et al. Evaluation of a biomethane, food and biofertiliser polygeneration system in a circular economy system. Renewable and Sustainable Energy Reviews. 2022 Dec 1;170:112960.

5. Price PR, Mcmullin B, O'dochartaigh A. International Conference on Negative CO2 Emissions. [cited 2023 Feb 2]. Methane mitigation achievement, including agriculture, is crucial to limiting dependence on uncertain carbon dioxide removal in national carbon budgeting equitably meeting Paris goals. Available from: https://doras.dcu.ie/27349/

6. Eory V, Topp CFE, Moran D. Multiple-pollutant cost-effectiveness of greenhouse gas mitigation measures in the UK agriculture. Environ Sci Policy. 2013 Mar 1;27:55–67.

7. Aertsens J, De Nocker L, Gobin A. Valuing the carbon sequestration potential for European agriculture. Land use policy. 2013 Mar 1;31:584–94.

8. Mceldowney J. EU agricultural policy and climate change [Internet]. 2020 [cited 2022 Apr 20]. Available from: https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/651922/EPRS_BRI(2020)651922_EN.pdf

9. Liebetrau J, Wellisch M, Lyng KA, Bochmann G, McCabe BK, Harris PW, et al. Potential and utilization of manure to generate biogas in seven countries [Internet]. 2021 [cited 2022 Apr 20]. Available from:

https://www.ieabioenergy.com/wp-content/uploads/2021/07/Potential-utilization_WEB_END_NEW.pdf

10. Murthy GS. Techno-economic Assessment. In: Bioenergy : principles and applications. Wiley-Blackwell; 2016. p. 507–18.

11. Murthy GS. Life-Cycle Assessment. In: Bioenergy : principles and applications. Wiley-Blackwell; 2016. p. 521–43.

12. Bacenetti J, Fusi A, Azapagic A. Environmental sustainability of integrating the organic Rankin cycle with anaerobic digestion and combined heat and power generation. Science of The Total Environment. 2019 Mar 25;658:684–96.

13. Moran D, Macleod M, Wall E, Eory V, McVittie A, Barnes A, et al. Marginal Abatement Cost Curves for UK Agricultural Greenhouse Gas Emissions. J Agric Econ [Internet]. 2011 Feb 1 [cited 2022 Oct 26];62(1):93–118. Available from: https://onlinelibrary-wiley-com.ucc.idm.oclc.org/doi/full/10.1111/j.1477-9552.2010.00268.x

14. Government of Ireland. Climate Action Plan 2019 [Internet]. 2019 [cited 2022 Jul 13]. Available from: https://www.gov.ie/en/publication/ccb2e0-the-climate-action-plan-2019/

15. Lanigan GJ, Donnellan T, Lanigan G, Hanrahan K, Paul C, Shalloo L, et al. An Analysis of Abatement Potential of Greenhouse Gas Emissions in Irish Agriculture 2021-2030 Prepared by the Teagasc Greenhouse Gas Working Group Authors. 2019;

16. Central Statistics Office. Farm Structure - CSO [Internet]. 2021 [cited 2022 Sep 20]. Available from: https://www.cso.ie/en/releasesandpublications/ep/p-coa/censusofagriculture2020-preliminaryresults/farmstructure/

17. Dillon E, Donnellan T, Moran B, Lennon J. Teagasc National Farm Survey 2020 Results Rural Economy Development Programme Acknowledgements. 2021;

18. Hennessy T, Moran B, Thorne F. Why Dairying?

19. European Commission. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) [Internet]. 2018 [cited 2022 Jul 21]. Available from: https://eur-lex.europa.eu/legal-

content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC

20. van den Oever AEM, Cardellini G, Sels BF, Messagie M. Life cycle environmental impacts of compressed biogas production through anaerobic digestion of manure and municipal organic waste. J Clean Prod. 2021 Jul 15;306:127156.

21. Long A, Murphy JD. 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. 2019 Nov 1;115:109347.

22. O'Shea R, Wall D, Kilgallon I, Murphy JD. Assessment of the impact of incentives and of scale on the build order and location of biomethane facilities and the feedstock they utilise. Appl Energy. 2016 Nov 15;182:394–408.

23. O'Shea R, Lin R, Wall DM, Browne JD, Murphy JD. Using biogas to reduce natural gas consumption and greenhouse gas emissions at a large distillery. Appl Energy. 2020 Dec 1;279:115812.

24. O'Shea R, Wall DM, Kilgallon I, Browne JD, Murphy JD. Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region. Appl Energy. 2017 Feb 15;188:237–56.

25. Allen E, Wall DM, Herrmann C, Murphy JD. A detailed assessment of resource of biomethane from first, second and third generation substrates. Renew Energy. 2016 Mar 1;87:656–65.

26. Liebetrau J, Clemens J, Cuhls C, Hafermann C. Methane emissions from biogas-producing facilities within the agricultural sector. Eng Life Sci [Internet]. 2010 [cited 2022 Dec 6];10(6):595–9. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/elsc.201000070?casa_token=McPVFCtGSxwAAAAA:igXy_XypY3X7X3k83pDalpwCqQE6zv-c3VWymWffITc3KOto6sIOjqFcvutf-zGQdfLQIVk6zzJfqQ

27. van den Oever AEM, Cardellini G, Sels BF, Messagie M. Life cycle environmental impacts of compressed biogas production through anaerobic digestion of manure and municipal organic waste. J Clean Prod. 2021 Jul 15;306:127156.

28. Deng C, Lin R, Kang X, Wu B, O'Shea R, Murphy JD. Improving gaseous biofuel yield from seaweed through a cascading circular bioenergy system integrating anaerobic digestion and pyrolysis. Renewable and Sustainable Energy Reviews. 2020 Aug 1;128:109895.

29. Power NM, Murphy JD. Which is the preferable transport fuel on a greenhouse gas basis; biomethane or ethanol? Biomass Bioenergy. 2009 Oct 1;33(10):1403–12.

30. Murphy JD, McKeogh E, Kiely G. Technical/economic/environmental analysis of biogas utilisation. Appl Energy. 2004 Apr 1;77(4):407–27.

31. O'Shea R, Wall DM, Kilgallon I, Browne JD, Murphy JD. Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region. Appl Energy. 2017 Feb 15;188:237–56.

32. Element Energy, Ricardo Energy and Environment. District Heating and Cooling National Heat Study Spatial Analysis of Infrastructure Costs and Potential in Ireland [Internet]. 2022 Feb [cited 2023 Apr 28]. Available from: https://www.seai.ie/publications/District-Heating-and-Cooling.pdf

33. Bruton T. A Guide to District Heating in Ireland [Internet]. 2016 [cited 2022 Sep 20]. Available from: https://www.seai.ie/publications/2016_RDD_79._Guide_District_Heating_Irl_-_CODEMA.pdf

34. Wu B, Lin R, O'Shea R, Deng C, Rajendran K, Murphy JD. Production of advanced fuels through integration of biological, thermo-chemical and power to gas technologies in a circular cascading bio-based system. Renewable and Sustainable Energy Reviews. 2021 Jan 1;135:110371.

35. O'Connor S, Ehimen E, Pillai SC, Black A, Tormey D, Bartlett J. Biogas production from small-scale anaerobic digestion plants on European farms. Renewable and Sustainable Energy Reviews. 2021 Apr 1;139:110580.

36. Dennehy C, Lawlor PG, Gardiner GE, Jiang Y, Shalloo L, Zhan X. Stochastic modelling of the economic viability of on-farm co-digestion of pig manure and food waste in Ireland. Appl Energy. 2017 Nov 1;205:1528–37.

37. O'Connor S, Ehimen E, Pillai SC, Lyons G, Bartlett J. Economic and Environmental Analysis of Small-Scale Anaerobic Digestion Plants on Irish Dairy Farms. Energies 2020, Vol 13, Page 637 [Internet]. 2020 Feb 3 [cited 2022 May 23];13(3):637. Available from: https://www.mdpi.com/1996-1073/13/3/637/htm

38. Villarroel-Schneider J, Mainali B, Martí-Herrero J, Malmquist A, Martin A, Alejo L. Biogas based polygeneration plant options utilizing dairy farms waste: A Bolivian case. Sustainable Energy Technologies and Assessments. 2020 Feb 1;37:100571.

39. Bauer F, Hulteberg C, Persson T, Tamm D. Biogas upgrading-Review of commercial technologies; Biogasuppgradering-Granskning av kommersiella tekniker. 2013 [cited 2022 Jun 15]; Available from: https://www.osti.gov/etdeweb/biblio/22090519

40. Debt Interest | NTMA [Internet]. [cited 2022 Sep 27]. Available from: https://www.ntma.ie/business-areas/funding-and-debt-management/statistics/debt-interest

41. Statista. Ireland - Inflation rate 2027 [Internet]. 2023 [cited 2022 Sep 27]. Available from: https://www.statista.com/statistics/375229/inflation-rate-in-ireland/

42. de Dobbelaere A, Keulenaere B, de Mey J, Lebuf V, Meers E, Ryckaert B, et al. Small-scale anaerobic digestion : case studies in Western Europe. 2015.

43. Vo TTQ, Wall DM, Ring D, Rajendran K, Murphy JD. Techno-economic analysis of biogas upgrading via amine scrubber, carbon capture and ex-situ methanation. Appl Energy. 2018 Feb 15;212:1191–202.

44. The cost of producing home-grown feeds - Teagasc | Agriculture and Food Development Authority [Internet]. [cited 2022 Sep 20]. Available from: https://www.teagasc.ie/animals/beef/grange/beef2022-open-day/the-cost-of-producing-home-grown-feeds--/

45. Rajendran K, Browne JD, Murphy JD. What is the level of incentivisation required for biomethane upgrading technologies with carbon capture and reuse? Renew Energy. 2019 Apr 1;133:951–63.

46. SEAI. Support Scheme for Renewable Heat Scheme Overview [Internet]. 2019 [cited 2022 Aug 1]. Available from: https://www.seai.ie/publications/SSRH-Scheme-Details-.pdf

47. EIRGRID. Renewable Electricity Support Scheme 1 RESS 1 Final Auction Results [Internet]. 2020 [cited 2022 Jul 1]. Available from: https://www.eirgridgroup.com/site-files/library/EirGrid/207158-EirGrid-Renewable-Energy-Scheme-LR5.pdf

48. SEAI. Prices - Energy Statistics In Ireland [Internet]. 2022 [cited 2022 Aug 12]. Available from: https://www.seai.ie/data-and-insights/seai-statistics/key-statistics/prices/

49. Short W, Packey D, Holt T. A manual for the economic evaluation of energy efficiency and renewable energy technologies. 1995 [cited 2022 Sep 20]; Available from: https://www.osti.gov/biblio/35391

50. Kvist T, Aryal N. Methane loss from commercially operating biogas upgrading plants. Waste Management. 2019 Mar 15;87:295–300.

51. Krey V, Masera O, Blanford USA G, Bruckner T, Cooke R, Fisher-Vanden K, et al. Annex II: Metrics & Methodology. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. 2014;

52. Public Spending Code. Supplementary Guidance - Measuring & Valuing Changes in Greenhouse Gas Emissions in Economic Appraisal [Internet]. Dublin; 2019 [cited 2022 Aug 5]. Available from: https://www.gov.ie/en/publication/public-spending-code/

53. Himanshu H, Murphy JD, Lenehan JJ, O'Kiely P. Impacts of characteristics of grass silage and cattle slurry feedstocks on the cost of methane production. Biofuels, Bioproducts and Biorefining [Internet]. 2019 Jan 1 [cited 2023 Jan 17];13(1):129–39. Available from: https://onlinelibrary-wiley-com.ucc.idm.oclc.org/doi/full/10.1002/bbb.1947

54. Electric Ireland to up gas and electricity prices again [Internet]. [cited 2022 Oct 2]. Available from: https://www.rte.ie/news/business/2022/0901/1320041-electric-ireland-price-hike/

55. Government of Ireland. Government agrees to the introduction of an obligation on the heat sector by 2024 [Internet]. [cited 2023 May 2]. Available from: https://www.gov.ie/en/press-release/83757-government-agrees-to-the-introduction-of-an-obligation-on-the-heat-sector-by-2024/

56. Government of Ireland. Climate Action Plan 2023 [Internet]. 2023 [cited 2023 May 2]. Available from: https://www.gov.ie/en/publication/7bd8c-climate-action-plan-2023/

57. Ó Céileachair D, O'Shea R, Murphy JD, Wall DM. Alternative energy management strategies for large industry in non-gas-grid regions using on-farm biomethane. Appl Energy. 2021 Dec 1;303:117627.

58. Singh P, Kalamdhad AS. Assessment of small-scale biogas digesters and its impact on the household cooking sector in India: Environmental-resource-economic analysis. Energy for Sustainable Development. 2022 Oct 1;70:170–80.

59. Onwosi CO, Ozoegwu CG, Nwagu TN, Nwobodo TN, Eke IE, Igbokwe VC, et al. Cattle manure as a sustainable bioenergy source: Prospects and environmental impacts of its utilization as a major feedstock in Nigeria. Bioresour Technol Rep. 2022 Sep 1;19:101151.

60. Villarroel-Schneider J, Mainali B, Martí-Herrero J, Malmquist A, Martin A, Alejo L. Biogas based polygeneration plant options utilizing dairy farms waste: A Bolivian case. Sustainable Energy Technologies and Assessments. 2020 Feb 1;37:100571.

61. Jones P, Salter A. Modelling the economics of farm-based anaerobic digestion in a UK whole-farm context. Energy Policy. 2013 Nov 1;62:215–25.

62. Tan WE, Liew PY, Tan LS, Woon KS, Mohammad Rozali NE, Ho WS, et al. Life Cycle Assessment and Techno-Economic Analysis for Anaerobic Digestion as Cow Manure Management System. Energies (Basel) [Internet]. 2022 Dec 1 [cited 2023 May 5];15(24):9586. Available from: https://www.mdpi.com/1996-1073/15/24/9586/htm

63. Imeni SM, Puy N, Ovejero J, Busquets AM, Bartroli J, Pelaz L, et al. Techno-Economic Assessment of Anaerobic Co-digestion of Cattle Manure and Wheat Straw (Raw and Pre-treated) at Small to Medium Dairy Cattle Farms. Waste Biomass Valorization [Internet]. 2020 Aug 1 [cited 2023 May 5];11(8):4035–51. Available from: https://link.springer.com/article/10.1007/s12649-019-00728-4

64. Wu B, Lin R, O'Shea R, Deng C, Rajendran K, Murphy JD. Production of advanced fuels through integration of biological, thermo-chemical and power to gas technologies in a circular cascading bio-based system. Renewable and Sustainable Energy Reviews. 2021 Jan 1;135:110371.

65. Koutra E, Economou CN, Tsafrakidou P, Kornaros M. Bio-Based Products from Microalgae Cultivated in Digestates. Trends Biotechnol. 2018 Aug 1;36(8):819–33.

66. Stiles WAV, Styles D, Chapman SP, Esteves S, Bywater A, Melville L, et al. Using microalgae in the circular economy to valorise anaerobic digestate: challenges and opportunities. Bioresour Technol. 2018 Nov 1;267:732–42.

67. Bose A, O'Shea R, Lin R, Long A, Rajendran K, Wall D, et al. The marginal abatement cost of co-producing biomethane, food and biofertiliser in a circular economy system. Renewable and Sustainable Energy Reviews [Internet]. 2022 Nov 1 [cited 2022 Nov 1];169:112946. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1364032122008279

68. Bose A, O'Shea R, Lin R, Long A, Rajendran K, Wall D, et al. Evaluation of a biomethane, food and biofertiliser polygeneration system in a circular economy system. Renewable and Sustainable Energy Reviews. 2022 Dec 1;170:112960.

69. Oreggioni GD, Luberti M, Tassou SA. Agricultural greenhouse CO2 utilization in anaerobic-digestion-based biomethane production plants: A techno-economic and environmental assessment and comparison with CO2 geological storage. Appl Energy. 2019 May 15;242:1753–66.

70. Ravina M, Genon G. Global and local emissions of a biogas plant considering the production of biomethane as an alternative end-use solution. J Clean Prod. 2015 Sep 1;102:115–26.

71. KPMG, Devenish, Gas Networks Ireland. Sustainability of Biomethane Production in Ireland Exploring how Ireland can deliver a sustainable, agriculture-led biomethane industry [Internet]. 2021 [cited 2022 Jul 21]. Available from: https://www.gasnetworks.ie/biomethane-sustainability-report-2021.pdf

72. Greenhouse gas emissions and projections | Environmental Protection Agency [Internet]. [cited 2023 Feb 2]. Available from: https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/

73. Ó Céileachair D, O'Shea R, Murphy JD, Wall DM. The effect of seasonal biomass availability and energy demand on the operation of an on-farm biomethane plant. J Clean Prod. 2022 Sep 25;368:133129.

74. gov.ie - Renewable Energy Feed-in Tariff (REFIT) Scheme [Internet]. [cited 2022 Oct 2]. Available from: https://www.gov.ie/en/publication/9bf994-renewable-energy-feed-in-tariff-refit-scheme/

5 Probabilistic analysis of the abatement cost and potential of on-farm anaerobic digestion in Ireland

Probabilistic analysis of the abatement cost and potential of on-farm anaerobic digestion in Ireland.

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Abstract:

There is a need to reduce dependence on fossil-derived natural gas to meet net zero targets. For example, Ireland has a climate action plan which includes for generation of 5.7 TWh of biomethane by 2030. It is crucial to understand financial and environmental barriers for the introduction of anaerobic digestion facilities. Recent geopolitical events emphasise the need to consider energy price uncertainty, which impacts on anaerobic digestion system costs. Abatement cost curves allow comparison of system viability but may overlook uncertainty. This study introduces an illustrative approach, factoring in uncertainty, for comparing farm scale anaerobic digestion systems by biogas end-use configuration, and by herd size. Probability charts derived from a Monte Carlo analysis were developed, altering different input variables that directly impact on the financial viability and the environmental performance of the systems. It was found that the energy conversion efficiency of the feedstock in the anaerobic digestion process directly affected the financial and environmental performance of all scenarios. Furthermore, based on the assumptions of this work, systems considering the production of electricity and heat using a CHP unit had a high probability of achieving lower abatement cost. For instance, a scenario with 185 dairy cows could achieve an abatement cost between -140 to 200 € tCO_{2eq}^{-1}. The scenarios that considered an upgrading configuration proved to be not financially viable, with high uncertainty in the abatement cost range. To make small-scale upgrading more attractive, additional incentivisation and revenue streams, or the integration of a CHP unit to cover the energy demand of the system would be required.

Keywords: Anaerobic Digestion; Techno-Economic Assessment; Sensitivity analysis; Abatement Cost; Uncertainty analysis.

5.1 Introduction

As per Ireland's Climate Action Plan 2023, the expansion of the anaerobic digestion (AD) and biomethane sector has been identified as a measure to abate greenhouse gas (GHG) emissions from agriculture (1). A target of 5.7 TWh of biomethane by 2030 has been set, which equates to the construction of approximately 200 new AD plants at a scale of 3 MW of biomethane output (1). AD at a farm-level can reduce GHG emissions while producing on-site renewable energy, a nutrient-rich biofertiliser (digestate), and mitigate odours and pathogen loads by reducing raw slurry application to land (2). Furthermore, as a response to the disruption in the global energy market, due to recent geo-political events, the EU presented the REPowerEU Action Plan that aims to reduce the dependency on Russian natural gas by highlighting the importance of renewable energy sources, particularly biomethane (3). To decrease dependence on fossil-derived natural gas, there has already been a significant increase in the number of AD plants in Europe since 2011. Biomethane plants increased six-fold since 2011 with 900 installations producing 32 TWh by 2020 in Europe, this production will increase with the construction of 92 new facilities in 2021 (4). To put this in context the REPowerEU Action Plan sets a 2030 target for biomethane of 35 billion cubic meters (bcm); this is equivalent to 350 TWh, a tenfold increase on present levels of production (3). In Ireland, development has been slow with only 59 AD plants operational by 2018, of which 3 produce biomethane with a total annual production of 22.8 GWh (5). To achieve the ambitions to increase AD uptake in Ireland it will be necessary to understand the main financial barriers and the policies, incentives, and regulations required to encourage growth.

Previous studies have identified the potential of co-digesting grass silage and cattle slurry to produce biomethane in Ireland (6–8). Ireland had 6.5 million cattle in 2020, of which 1.5 million were dairy cows, thus it is considered that there are significant quantities of slurry available as feedstock (9). In relation to grass silage, most of the production is directed to feed livestock during winter. That said, grass surplus to livestock requirements (10), or grass obtained as a by-product of landscape management from non-pasture areas have been identified as viable feedstock for AD (11–13). To cover the nitrogen (N) requirement to grow grass silage, synthetic fertiliser (inorganic N) and slurry (organic N) are applied to the land. However, recent geo-political events have seen an unprecedented increase in fuel prices and the costs associated with synthetic fertiliser, thus leading to rising costs for grass silage (14). This directly impacts the production cost of biomethane, since feedstock costs can represent up to half of the biogas production cost at a farm-scale AD facility (15).

The majority of biogas generated in Ireland is used for the production of electricity and/or heat through boilers or combined heat and power units (CHP) (16). However, a national biomethane strategy is due to be released and is intended to mobilise the biomethane industry. This will include for a Renewable Heat Obligation to encourage the use of indigenously produced biomethane (1). Furthermore, the gas grid operator, Gas Networks Ireland, aims to develop a biomethane network of rural on-farm AD facilities injecting biomethane into the gas grid (17,18). In 2022, energy prices reached a peak price of €250 per MWh for electricity and €500 per MWh for natural gas (19). This uncertainty in energy prices directly influences the value of energy produced by on-farm AD systems. Depending on the energy requirements of the process, and/or the upgrading technology from biogas to biomethane, additional costs may be incurred from sudden increases in energy prices.

To achieve the desired number of biomethane facilities in Ireland by 2030 (200 AD plants) it is essential to evaluate the feasibility of on-farm AD installations that would comply with the sustainability criteria set by the recast Renewable Energy Directive (RED-II) (20). A techno-economic assessment (TEA) can be used to assess the economic performance of an AD system (21), whilst the sustainability of the system can be measured through a Life Cycle Assessment (LCA), based on a GHG emissions assessment (21,22). The abatement cost can subsequently be calculated by combining the financial and sustainability data and presenting as an abatement cost curve (22). Abatement cost curves are commonly used to compare climate mitigation policies as they provide simple models that compare different abatement options in various sectors of the economy (22). Biogas and biomethane abatement costs were evaluated previously as a bioenergy GHG mitigation measure to decarbonise agriculture in Ireland (23). The use of biogas to generate heat and electricity was assessed with an abatement cost of 115 € tCO_{2eq}^{-1}, while that of biomethane to produce renewable heat was assessed at 280 € tCO_{2eq}^{-1} (23). A recent update of these measures decreased the abatement cost of biomethane to -198 € tCO_{2eq}^{-1} (linear uptake of measure) and -219 € tCO_{2eq}^{-1} (double uptake of measure) accounting for an increase in the selling prices of heat and gas due to recent geo-political events (24).This variability in abatement costs has been previously assessed by the authors (25), where it was found that even a change in a single input variable within the system boundary of the study can significantly affect the abatement cost and potential of on-farm AD.

With the recent increases in energy and fertiliser prices, it must now be considered how external events can introduce uncertainty in the calculation of the abatement cost for anaerobic digestion systems. Previous studies have accounted for the impact of parameter uncertainty on the financial viability of anaerobic digestion by including uncertainty analysis using a Monte Carlo approach (26,27). These specific studies remarked on the importance of uncertainty quantification which provides probabilistic results that can be far more demonstrative of the potential economic viability of an AD system than single-point estimations. In Ireland, the use of uncertainty analysis to evaluate the financial viability of on-farm AD plants has been completed previously by Dennehy et al. (28) for the mono-digestion of pig slurry and its co-digestion with food waste. As part of the analysis, four input variables - gate fees, digestate disposal cost, feed-in-tariffs and annual feedstock treated - were varied, assuming future market conditions, to evaluate their effect on profitability. It was found that, even in high revenue generation scenarios, the system profitability can still be influenced by market conditions such as feedstock availability. In essence, evaluating the financial feasibility of a project in a changing market through the integration of uncertainty modelling can provide crucial information to AD developers. The integration of uncertainty analysis may be beneficial in identifying if further incentives or additional sources of income are required to integrate AD in farms.

Further studies have assessed abatement cost curves for alternative mitigation technologies accounting for uncertainty. *Peng et al.*(29) and *Sjöstrand et al.* (30) presented abatement cost curves accounting for uncertainty for the transport sector and for water scarcity mitigation efforts. However, these analyses solely considered uncertainty in the abatement cost calculation and did not account for its impact on the abatement potential of the measures. In terms of AD systems, the uncertainty in the abatement cost has only been assessed previously in a study by *Bose et al.* (31)

that explored the uncertainty of an AD polygeneration plant. Prior research has presented limited approaches to depict and compare the uncertainty in both abatement cost and potential. There is a need to provide a more illustrative approach that can integrate both the uncertainties of the abatement cost and potential of a technology such as anaerobic digestion.

The aim of this study is to identify the uncertainty associated with different biogas end uses from on-farm AD systems. The novelty of this work is the development of probability charts to compare the abatement cost and abatement potential, whilst accounting for uncertainty, of different on-farm AD systems based on biogas end-use at different farm sizes. These probability charts will serve as a valuable tool for comparing AD systems based on the range of possible abatement costs, providing insights for stakeholders such as farmers, system developers, and policy makers to identify economically feasible options of technology implementation. Furthermore, this study aims to assist policymakers in recognising the potential incentives required for systems with high uncertainty, thus informing the development of energy policies that can effectively support the widespread adoption of on-farm AD. Three specific objectives are outlined for this study:

- Identify through a sensitivity analysis the key financial and environmental variables affecting the abatement cost for on-farm AD systems.
- Evaluate the potential ranges of abatement cost and abatement potential for different biogas end-uses at different farm scales through Monte Carlo analysis.
- Assess the results of the Monte Carlo analysis based on the overall uncertainty associated with the abatement cost and abatement potential to identify if additional incentives are required for on-farm AD systems

5.2 Methodology

5.2.1 Model description and base case scenarios

For the on-farm base case scenarios, four hypothetical farm sizes based on different herd sizes of dairy cows (40, 60, 100, 185) were combined with 4 different biogas end-use configurations for a total of 16 scenarios as shown in Table 5-1, as previously assessed in Chapter 4. The configurations include the use of biogas to produce heat through a boiler unit (B), the production of electricity and heat through a CHP unit (CHP), the production of biomethane through upgrading (U), and the production of biomethane with the use of a CHP unit to provide the energy demand of the upgrading process (U+CHP). These scenarios were selected to study the influence of different input variables of the on-farm AD process on the financial viability and the environmental performance through the calculation of the abatement cost.

Table 5-11 Base case scenarios for the on-farm AD systems at different farm scales based on the biogas end-use.

Farm Size	Configuration	Scenario Code
40	Boiler	B-40
	CHP	CHP-40
	Upgrading	U-40
	U+CHP	U+CHP40
60	Boiler	B-60
	CHP	CHP-60
	Upgrading	U-60
	U+CHP	U+CHP60
100	Boiler	B-100
	CHP	CHP-100
	Upgrading	U-100
	U+CHP	U+CHP100
185	Boiler	B-185
	CHP	CHP-185
	Upgrading	U-185
	U+CHP	U+CHP-185

The main input variables that will be assessed for each base case scenario include the farm conditions, the operational parameters of the AD digester, and the economic assumptions that include the revenues and cost of each scenario based on the biogas end-use configuration. The main output variables of the model are the net present value (NPV), the abatement cost, and abatement potential for each scenario. A sensitivity analysis will be carried out on 24 selected input variables to identify the key factors influencing the NPV, the abatement cost, and the abatement potential.

Based on the results of the sensitivity analysis, the most sensitive variables affecting the abatement cost will be selected for use in the uncertainty analysis.

To assess the uncertainty of each scenario an enviro-economic tool previously developed for on-farm AD (25) was integrated with Monte Carlo analysis using @Risk, a plugin developed by Lumivero for MS Excel (32). For each input variable, a probability distribution is assigned to carry out a Monte Carlo analysis. Triangular and Uniform distributions were selected for the Monte Carlo assessment as these are recommended when there is limited access to data for emerging technologies (33,34). Triangular distributions require three main parameters which include the upper bound (maximum value), the lower bound (minimum value), and most likely value (median) while the uniform distribution only requires upper and lower bounds. With the result of the analysis, a probability chart of the abatement cost and potential will be created to outline the ranges of values each of the different systems can achieve based on the biogas end-use at different farm scales.

5.2.2 Farm conditions and feedstock resources

The farmland area for the base case scenarios was based on 4 different herd sizes (40, 60, 100, 185) which represent the typical dairy cow herd sizes on dairy farms in Ireland (35). For each herd, the farmland area in hectares was selected based on the median farm size of utilised agricultural area at different scales for dairy farms in Ireland (27.8 ha, 44.4 ha, 72.9 ha, 136.2 ha) (36). For each farm, it was assumed that part of the farmland was dedicated for pasture based on the requirements per dairy cow with a stocking rate of 2.06 lu ha^{-1} (livestock units per hectare). Based on this the remaining number of hectares, surplus to livestock requirements (H_{GS}) was assumed to be used to cultivate grass silage for use in the AD process as per Equation 5-1.

Equation 5-1 Hectares available to cultivate grass silage in each farm.

$$H_{GS}\left(\frac{\mathrm{ha}}{\mathrm{a}}\right) = AA_{farm} - (\theta_{DC} * SR_{DC})$$

Where, AA_{farm} is the available agricultural area on the farm, θ_{DC} is the number of dairy cows, and SR_{DC} is the stocking rate of grazed grass required for feeding each dairy cow across the farm.

In Ireland, livestock are commonly housed indoors during the winter period, ranging between 16 to 22 weeks each year, depending on the region, as guided by Good

Agricultural Practices (GAP) (32). Slurry collection needs to comply with the slurry storage requirements of 0.33 m^3 per week per dairy cow (37). For the base case scenarios, it was assumed that the dairy cows would be housed for 18 weeks (as per Table 5-2), and that the slurry collected would be based on 0.33 t_{wwt} per week, as it mostly consists of water based on the dry matter (DM) content (as per Table 5-3). Based on this the total amount of slurry available as feedstock (DS_R) in terms of wet tonnes (t_{wwt}) per year was calculated using Equation 5.2.

Equation 5-2 Dairy Slurry resource calculation.

$$DS_R\left(\frac{t_{wwt}}{a}\right) = \theta_{DC} * ST_{DC} * TH_{DC}$$

Where, DS_R is the mass of slurry feedstock in tonnes, θ_{DC} represents the number of dairy cows on each farm, ST_{DC} is the slurry collection requirements per dairy cow in t_{wwt} per week, and TH_{DC} is the time in weeks dairy cows are housed indoors per year.

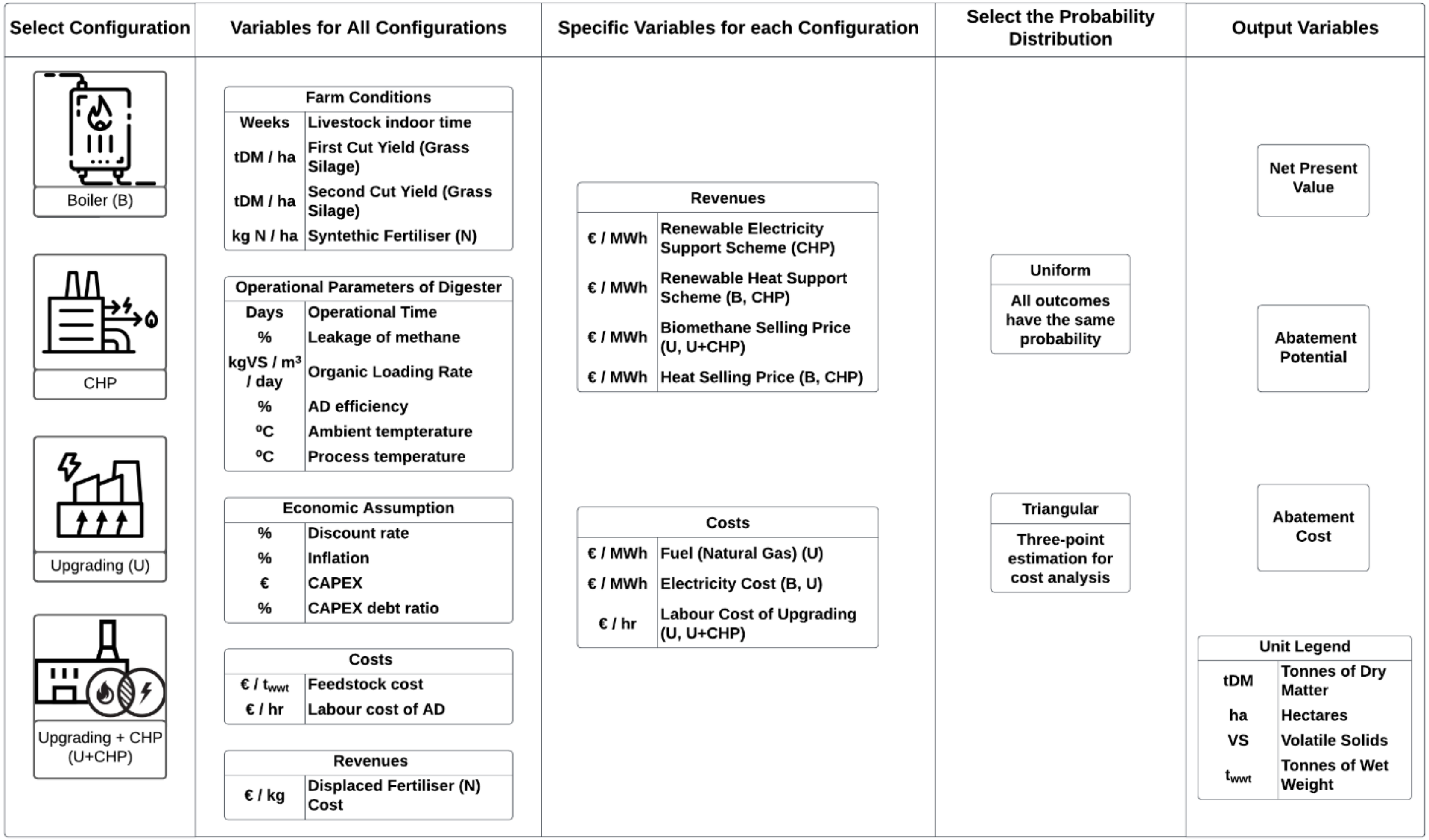

Figure 5-3 Summary of the model used for the base case scenarios considering 4-biogas end-uses (Boiler- B, CHP, Upgrading- U and Upgrading+CHP-U+CHP) for the on-farm anaerobic digestion scenarios. 24 input variables that include farm conditions, operational parameters of the digester and economic assumptions (revenues and cost) were selected to identify key factors influencing the output variables (NPV, abatement cost, and abatement potential) through sensitivity analysis.

Table 5-12 Farm conditions for the 16 base case scenarios of on-farm AD.

Variable	Value	Source
Livestock Indoor Time [Weeks]	18	(38)
First Cut Yield (Grass Silage) [tDM ha^{-1}]	7	(10)
Second Cut Yield (Grass Silage) [tDM ha^{-1}]	4	(39)
Synthetic Fertiliser (N requirement) [kg N ha^{-1}]	185	(40)

Table 5-13 Feedstock characteristics. Adapted from Allen et al. (41).

Parameter	Cattle Slurry	Grass Silage 1st Cut	Grass Silage 2nd Cut
Dry Matter (DM) [%]	6.50	29.30	17.90
Volatile solids (VS[a]) [%]	5.10	26.80	16.40
VS / DM [%]	78.50	91.70	92.00
Specific methane yield (SMY) [LCH_4 $kgVS^{-1}$]	175.5	400	393
CH_4 in biogas (v/v) [%]	56	53	53

[a] VS: Volatile solids.
[b] (V/V): Volume concentration for volume of CH_4 per volume of biogas.

Grass silage production varies according to the region under analysis within Ireland and can range between 11 to 13 tDM ha^{-1} per annum (17,42–45). If the fertiliser application is maximised on the farm there can be an increase in grass production which facilitates obtaining grass silage surplus to livestock requirements (8). However, the GAP for Protection of Waters (S.I. No. 393/2022) limits the amount of fertiliser that can be applied to Irish dairy farms to 250 kg N fertiliser ha^{-1} a^{-1} of chemical fertiliser with the inclusion of organic fertiliser (46). For the base case scenarios, the mass in wet tonnes of grass silage for each cut (GS_R) was calculated using Equation 5-3. A value of 7 tonnes of dry matter per hectare (tDM ha^{-1}) was considered as the yield for the first cut of grass silage and 4 tDM ha^{-1} for the second cut. The amount of synthetic fertiliser required was set at 185 kg N ha^{-1} as per Table 5-2 based on the average application rate recommended for growing grass silage (40).

Equation 5-3 Grass Silage resource calculation.

$$GS_R\left(\frac{\mathrm{t_{wwt}}}{\mathrm{a}}\right) = \frac{(H_{GS} * Y^{Silage_{FC}})}{DM^{Silage_{FC}}/100} + \frac{(H_{GS} * Y^{Silage_{SC}})}{DM^{Silage_{SC}}/100}$$

For Equation 5-3, H_{GS} represents the hectares surplus to livestock feeding requirements, $Y^{Silage_{FC}}$ and $Y^{Silage_{SC}}$represents the yield of grass for each cut, and $DM^{Silage_{FC}}$ and $DM^{Silage_{SC}}$ represents the content of dry matter for each cut expressed as a decimal as per Table 5-3.

5.2.3 Operational parameters for biogas production and biogas end-use

The production of biogas was modelled on a continuously stirred tank reactor (CSTR) commonly used for farm-based AD plants (47–49). The gross biogas output from the AD plant was calculated from the co-digestion of slurry and grass silage using the respective feedstock specific methane yield (SMY) (as per Table 5-3) at an organic loading rate (ORL) of 2.5 kg VS m^{-3} day^{-1} under mesophilic conditions (35–40 °C) (50). Detailed calculations of the biogas output production can be found in Appendix B.2. For the base case scenarios as per Table 5-4, a complete energy conversion efficiency of feedstock in the AD process was considered to provide an optimistic analysis. This value (AD efficiency) is defined in this work as the specific methane yield achieved in a commercial process as compared to the results from a lab-scale experiment. This variable is directly affected by a variety of characteristics, such as feedstock composition, technology implementation and overall process conditions. Finally, the methane leakage for the AD system was set at 2% considering a minimal leakage of methane, as this value can range between 2 to 5% for biogas systems (51,52).

Table 5-14 Operational parameters of the anaerobic digestion process for the 16 base case scenarios of on-farm AD.

Variable	Value	Source
Operational Time of Reactor [Days]	344	(25)
Leakage of Methane [%]	2	(25)
ORL [kg VS m^{-3} day^{-1}]	2.5	(50)
Ambient Temperature [ºC]	10	Based on the annual average dry bulb temperature in Cork, Ireland (53).
Process Temperature [ºC]	40	(54)

For the base case scenarios each farm size was assigned a configuration based on the biogas end-use within the farm. A detailed description of each configuration can be found in Chapter 4.2.3 and is summarised below:

• The B Configuration generates heat using a biogas boiler for its immediate use in the vicinity of large industrial heat users or in district heating systems (if available). The heat generated was calculated based on the overall gross energy output of the biogas production at each farm size considering a boiler efficiency of 90% which is an average value for natural gas boilers (55,56). It was assumed the AD process covered its thermal demand using part of the heat generated, while the electricity demand was met by sourcing electricity from the grid.

• The CHP Configuration considered the production of electricity and heat using a CHP unit. The electricity and heat generated were calculated based on a 35% electrical efficiency and a 50% thermal efficiency based on a CHP with capacity less than 100kW_{el}, which is commonly used in small-scale systems (28,57–59). Part of the energy generated was assumed to cover the thermal demand and electrical demand of the AD process.

• The U Configuration considered the production of biomethane by upgrading the biogas produced via water scrubbing with the addition of a regenerative thermal oxidation unit for off-gas treatment. The biomethane production was calculated based on a 94% methane recovery of the gross biogas production (accounting for minimal process leakage) and an electrical demand of 0.45 kWh m^{-3} biogas considering previously reported data for small-scale systems (60). It was also assumed that the 6% of CH_4 not captured in the process would be contained in the liquid at the bottom of the scrubber and recirculated, and as such is not released to the atmosphere (61). The electrical demand of the AD and upgrading process was sourced with electricity from the grid, while the thermal demand was covered with a boiler using natural gas from the grid.

• Finally, the U+CHP Configuration considered the addition of a CHP unit to cover the electrical and thermal demand of the biogas production process and the upgrading process. This was considered to displace the use of fossil fuels and fossil derived energy sources so as to reduce the overall emissions of the configuration. Based on the required electrical power of the AD system and the upgrading process, the input volume of biogas for the CHP unit was calculated through an iterative process as detailed in section 4.2.3 of Chapter 4.

5.2.4 Economic assumptions

A techno-economic analysis was carried out to calculate the NPV for each of the base case scenarios. To evaluate the profitability of each different scenario the economic outputs were calculated based on a system lifetime of 15 years, which is common for on-farm AD systems (28,58). To calculate the NPV for each scenario the capital cost (CAPEX) of the system was deducted from the overall net cash flow which includes the revenues and operational costs (OPEX) of the configuration during the lifetime of the project as per Equation 5.4. A yearly inflation of 2% (62) was added to the revenues and OPEX to estimate yearly revenues and costs for each scenario. A 10-year loan with a 2% interest rate was considered for the CAPEX of each system with a debt ratio of 50% (Table 5-5) to cover the initial cost of the project (31).

Table 5-15 Economic assumptions for the 16 base case scenarios of on-farm AD.

Variable	Value	Source
Discount rate [%]	10	(63)
Inflation [%]	2	(62)
Capex Debt Ratio* [%]	50	(31)

*Ratio of the total debt to the total assets (CAPEX)

Equation 5-4 Net Present Value calculation.

$$NPV(€) = -C_o + \sum_{t=0}^{L} \frac{(C_i)}{(1+r)^t}$$

In Equation 5-4, C_o is the CAPEX of the configuration selected for the analysis, C_i represents the net cash flow period in the time t ($t \in [1, L]$), L denotes the lifetime of the selected systems in years, and r is the discount rate of 10% which is an average value for biogas facilities (63).

To calculate the CAPEX of each configuration the capital cost of AD systems previously installed in Ireland for which the feedstock processed was reported were used to get an approximated value of cost (€) per tonne of treated feedstock per year. The initial capital cost (C_o) used for each system was half of the total value of the cost for the developer (Table 5-6) considering a loan based on a capex-debt ratio of 50%. Detailed calculations of each capital cost can be found in Appendix B.7. For each plant, it was assumed that the required site works, infrastructure, and grid connection costs were included in the final cost.

Table 5-16 Capital Cost for each configuration based on the farm size for the 16 base case scenarios of on-farm AD.

Configuration \ Farm Size	40	60	100	185
B	€45,124	€76,692	€124,150	€233,880
CHP	€66,959	€113,802	€184,225	€347,053
U	€99,442	€169,009	€273,596	€515,414
U + CHP	€114,358	€194,360	€314,635	€592,725

The net cash flow per year (C_i) of each system accounted for the total cost of the system which included: the CAPEX, loan repayments, the insurance, administrative, and maintenance cost (see section 4.2.4 in Chapter 4), the OPEX and revenues generated by each configuration. The OPEX can be broken down into the labour cost required for the operation of the AD system and the upgrading system, and the annual expenses of fuel and electricity of the system based on the configuration of the base case scenario, and the feedstock acquisition cost as per Table 5-7. The labour cost of the AD process was applied to all configurations with an intensity set at 1hr/day, while the labour cost of upgrading which only applied to the U and U+CHP configurations, was set at 2hrs per day based on small-scale systems (64). The electricity expense only applied for the B and U scenarios as the scenarios with a CHP unit (CHP and U+CHP) covered the electricity demand of the system with part of the produced electricity. The cost of electricity was based on commercial electricity prices for Ireland in 2022 (65). Fuel expense only applied for the U configuration to cover the thermal demand of the AD process and biogas upgrading system with a natural gas boiler, as it was assumed that all the biomethane produce would be sold. Finally, the total feedstock procurement cost, based on the average silage cost for 2022 in Ireland (Table 5-7) and the procurement cost for slurry, was assumed to be 0 € t_{wwt}^{-1}, as slurry is produced on the farm.

Table 5-17 Operational cost values used for the 16 base case scenarios based on the configuration selected.

Variable	Value	Source
Labour cost of AD process [€ hr^{-1}]	15	(58)
Labour cost of Upgrading [€ hr^{-1}]	15	(58)
Fuel cost (Natural gas) [€ MWh^{-1}]	74.1	(65)
Electricity Cost [€ MWh^{-1}]	237 or 299*	(40)
Feedstock Cost (Silage) [€ t_{wwt}]	43	(14)

*Different electricity costs were used based on the range of consumption for each scenario. For consumption levels below 20 MWh a^{-1}, a cost of 299 € MWh^{-1} was applied, while consumption levels exceeding 20 MWh a^{-1} were considered at a cost of 237 € MWh^{-1}.

For revenues, each of the base case scenarios considered different sources of income based on the type of energy generated by the biogas end-use configuration while all the scenarios accounted for the use of digestate, a process output of the AD plant, to displace synthetic fertiliser (Table 5-8) based on its total nitrogen content (Table C-1 of Appendix C) assuming a 60% N availability (66). For configurations that generated heat (B and CHP), two sources of income were considered, a financial incentive by the Irish government in the form of the support scheme for renewable heat (SSRH) and the sale of heat based on a customer price for district heating (Table 5-8) (67,68). As only one configuration produced electricity (CHP), the support from the renewable electricity support scheme (RESS) was applied to it (Table 5-8) (69).

Both the SSRH and RESS provide up to 15 years of financial subsidies. Finally, the configurations that produced biomethane (U and U+CHP) considered a biomethane selling price comparable to the weighted average price of natural gas for business consumers in Ireland in the second half of 2022 (70).

Table 5-18 Revenues considered for the 16 base case scenarios.

Variable	Value	Source
RESS[a] [€ MWh^{-1}]	74.08	(67)
SSRH[b] [€ MWh^{-1}]	29.5	(69)
Biomethane selling price [€ MWh^{-1}]	53.7	(70)
Heat Selling Price [€ MWh^{-1}]	60	(68)
Displaced Fertiliser (N) cost [€ kg N^{-1}]	2.7	(14)

[a]RESS: Renewable Electricity Support Scheme
[b]SSRH: Support Scheme for Renewable Heat

5.2.5 Abatement cost calculation

To calculate the abatement cost, the overall annual GHG emissions savings (tCO_{2eq} a^{-1}) were calculated using the methodology recommended by the EU recast Renewable Energy Directive (RED-II) (20) with the modification to include emissions savings from the displacement of synthetic fertiliser (e_{fd}) and the emissions savings from energy displacement (e_{ed}) (Equation 5.5). GHG emissions related to the cultivation of feedstock ($e_{ec,n}$), transport ($e_{td,fd,n}$), and land use change ($e_{l,n}$) were calculated based on literature values (71). Emissions from processing (e_p) accounted for the direct emissions from energy use in the AD and upgrading processes and included for methane leaks in the process (during AD and biogas upgrading). Emissions from the transport of biomethane ($e_{td,product}$) were considered to be 1.22 gCO_{2eq} per $MJ_{biomethane}$ (71), while emission from fuel in use (e_u) were set as zero (short carbon cycle). Emissions savings from CO_2 capture and geological storage (e_{ccr}) and CO_2 capture and replacement of fossil fuels (e_{ccs}) were assumed to be zero and the emissions savings from agricultural management ($e_{sca,n}$) were set at -54 $kgCO_{2eq}$ per tonne of cattle slurry digested in line with the Renewable Energy Directive (20). Emissions savings from energy displacement (e_{ed}) considered the savings of emissions displaced from fossil fuel origin, accounting for the amount of heat and electricity generated by the B and CHP configurations, and for the emissions avoided by replacing diesel with biomethane (assuming biomethane will be used as transport fuel) for the U and U+CHP configurations. Finally, the emissions from the displacement of synthetic fertiliser

(e_{fd}) account for the reduction in emissions from synthetic fertiliser, due to the use of digestate as biofertiliser. The methodology used to determine the share of energy of each feedstock (S_n) has been provided in Chapter 4 (Section 4.2.5)

Equation 5-5 Annual emissions savings calculations for the base case scenario based on the REDII methodology to assess GHG emissions.

$$GHG_{conf,n} = \sum_{1}^{n} S_n \times \left(e_{ec,n} + e_{td,fd,n} + e_{l,n} - e_{sca,n}\right) + e_p + e_{td,product} + e_u - e_{ccs} - e_{ccr} - e_{fd} - e_{ed}$$

Once the economic (NPV) and environmental ($GHG_{conf,n}$) performance were obtained, the abatement cost (AC) of each base case scenario was evaluated according to Equation 5.6. The sum of the undiscounted annual GHG emissions ($GHG_{conf,n}^{t}$) of time period t was used to calculate the abatement potential or total GHG mitigation of each base case scenario, based on the lifetime of the system (L) ($t \in [1, L]$).

Equation 5-6 Abatement cost calculation.

$$AC\left(\frac{€}{t\ CO_{2-eq}}\right) = \frac{-NPV}{\sum_{t=1}^{L} GHG_{conf,n}^{t}}$$

In Ireland, a carbon tax is imposed on fuel supplies, which is determined by the carbon dioxide emissions generated when the fuel is utilised. As part of this analysis, the incentives required for the scenarios to reach a break-even with the carbon tax set for Ireland for 2030 (80 € tCO_2^{-1}) were explored (72). This analysis aims to determine if the AD systems assessed in the scenarios require economic incentives to make them competitive with paying a carbon tax on the fossil fuel alternatives. This assessment involved calculating the required NPV based on the total GHG mitigation of each base case scenario to match the value of the abatement cost to the carbon tax set for 2030. The NPV calculations were conducted using Microsoft Excel, employing the Goal Seek function to find the required incentive (€ MWh^{-1}) expressed as an additional income based on the net energy output of the configuration.

5.2.6 Sensitivity analysis and uncertainty analysis

A sensitivity analysis was conducted on the 24 variables previously presented across the 16 base case scenarios. These variables encompassed farm conditions, operational parameters of the AD digester, and economic assumptions involving costs and revenues associated with each configuration as shown in Figure 5-1. To assess their impact on key output variables, such as NPV, annual GHG emissions, and abatement cost, a ±10% variation was applied to each input variable. Based on the results, the variables that had more than a 5% impact on the abatement cost were selected to carry out uncertainty analysis. For this uncertainty analysis, a Monte Carlo simulation with 10,000 iterations was conducted to obtain a range of values for the NPV, the abatement cost and the abatement potential. Based on the type of variable selected for the analysis, a triangular or uniform distribution was assigned.

The simulation results were used to construct a probability chart, illustrating the uncertainty associated with the abatement cost and abatement potential for the 16 different scenarios. The 10,000 simulated outcomes will be interpreted in terms of the probability of the abatement cost and potential to fall within a specific range based on the results from the Monte Carlo analysis. This chart will provide a range of values for the abatement cost and potential for each scenario's outcomes based on the biogas end-use configuration. Figure 5-2 presents the step-by-step procedure used to develop the probability charts for each of the different scenarios.

To compare the results of each scenario, different probability intervals, including 25%, 75% and 95%, centred around the mean, were employed to estimate a range of values that describe a share of the simulation results. These values fall within typical ranges to assess the risk and uncertainty associated while comparing abatement strategies (29,73). To assess the dispersion of each of the ranges, the sampled interquartile range (IQR), mean, median and standard deviation will be assessed. The relationship between the standard deviation to the mean was used to compare the uncertainties associated with each biogas end-use configuration for all the scenarios. Lastly, significant differences between different biogas end-uses within scenarios were assessed using a Tukey-Kramer *post hoc* test through Microsoft Excel with an alpha level of <0.05. The test was carried out, for both the results from the abatement cost and abatement potential, to compare the similarities between biogas end-uses within the scenarios.

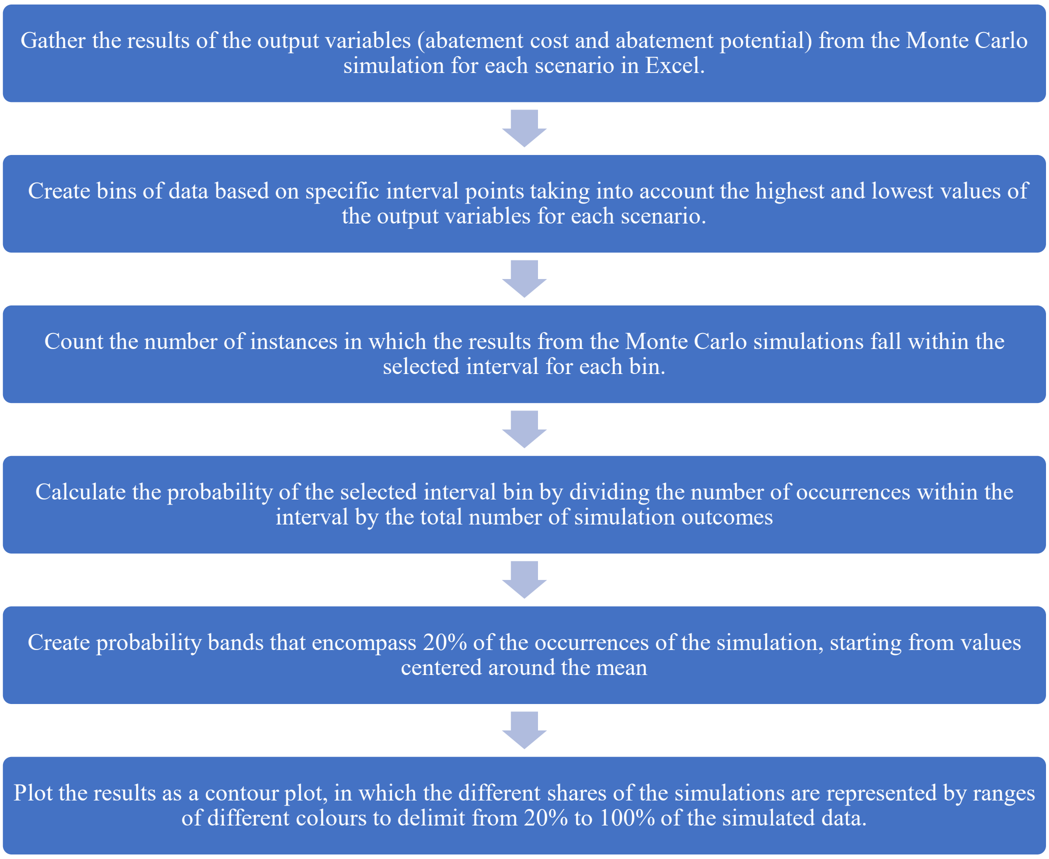

Figure 5-4 Flowchart of the process used to construct the probability chart based on the results of the Monte Carlo simulations.

5.3 Results

5.3.1 Base case scenario results

The results of the economic and environmental assessment for the 16 base case scenarios are shown in Table 5-9. It was found that most of the assessed scenarios were not financially viable, as evidenced by negative NPV values. However, the scenarios that considered the boiler configuration (B) for biogas end-use showed the best economic performance across the different farm sizes. Notably, the B-185 scenario was the only financially viable option across all scenarios which showed a positive NPV. The abatement cost of the scenarios ranged from -5 to 605 € tCO_{2eq}^{-1} for the 16 assessed scenarios. For the B and CHP configuration, most scenarios obtained abatement costs below the carbon tax set for Ireland for 2030 (80 € tCO_2^{-1}), apart from the CHP-60 scenario. Conversely, scenarios considering biogas upgrading displayed higher abatement costs, surpassing the carbon tax threshold. For these scenarios to achieve the required NPV (based on their GHG mitigation) to match the value of the abatement cost to the carbon tax, an incentive in the range of 68 to 116 € MWh^{-1} would be required. The results also demonstrated that the scale of the system exerts a substantial influence on the corresponding abatement cost, as evidenced by the decreasing abatement costs from scenarios with an increased farm scale, resulting from economies of scale. Detailed results from the AD process for the 4 farm scales can be found in Appendix C.1 and detailed results of the energy outputs and demands of the different configurations for the 16 base case scenarios can be found in Appendix C.2.

Table 5-19 Economic and environmental results of the 16 base case scenarios.

Scenario	NPV (€)	Total GHG Mitigation (tCO_{2eq})	Abatement Cost (€ tCO_{2eq}^{-1})
B-40	-€38,490	747	52
CHP-40	-€85,881	863	100
U-40	-€332,032	549	605
U+CHP40	-€296,334	764	388
B-60	-€26,261	1366	19
CHP-60	-€108,335	1573	69
U-60	-€476,889	1028	464
U+CHP60	-€415,306	1379	301
B-100	-€18,739	2192	9
CHP-100	-€147,037	2524	58
U-100	-€685,647	1662	413
U+CHP100	-€589,917	2203	268
B-185	€21,703	4193	-5
CHP-185	-€230,183	4821	48
U-185	-€1,172,633	3214	365
U+CHP-185	-€996,842	4184	238

5.3.2 Sensitivity analysis

The overall sensitivity results were similar across all base case scenarios. The results of the sensitivity assessment in terms of economic and environmental performance of the 4 biogas-end uses for one farm size (185 herd size) is shown in Figure 5-3 and Figure 5-4. Among all scenarios, the energy conversion efficiency of the AD process (AD efficiency) emerged as the most sensitive variable affecting the abatement cost. In particular, the B configuration (Figure 5-3) showed a high sensitivity, where a 10% increase in the efficiency of the process reduced the abatement cost by almost 450% from the base case scenario value of -5 € tCO_{2eq}^{-1} (Table 5-9).This enhancement of AD efficiency can be achieved with novel technologies such as microbial electrolysis cells (MEC), whereby the insertion of electrodes can increase the production of methane above the theoretical methane yield (74) or through addition of biochar which acts as an electron bridge and enhances yield while reducing time for process to take place (75). The sensitivity of abatement cost to AD efficiency was reduced for the CHP configuration to 50% and further reduced to 14% for the U and U+CHP configurations (Figure 5-4). Moreover, an increase of 10% in the efficiency improved the overall financial viability of the B and CHP configurations, as the NPV increased by 500% for the B-185 scenario and 44% for the CHP-185 scenario, with a marginal increase of 10% in the annual GHG emissions abated. In contrast, the increase in efficiency had a more pronounced impact on the annual GHG emissions abated for the scenarios with the U and

U+CHP configurations compared to its effect on the financial viability of the systems. The NPV only increased by 4%, while experiencing an 11% increase in emissions abated for the U configuration, while the U+CHP configuration had a 6% increase in NPV with a 9% rise in emissions abated.

Based on the results of the sensitivity analysis on the abatement cost, the most sensitive variables that affected the farm conditions across the configurations were the yield of grass silage from the first cut and the synthetic fertiliser required for its cultivation. In terms of operational parameters, the most sensitive variables included the efficiency of the AD process and methane leakage. Regarding economic assumptions, the most sensitive variables encompassed CAPEX, factors affecting the OPEX, revenues considered in the support schemes (SSRH and RESS), selling prices of energy (heat and biomethane), discount rate for the analysis, and feedstock cost of silage. The results of the sensitivity assessment for the herd sizes of 100, 60 and 40 can be found in Appendix C.3.

Figure 5-5 Results of the sensitivity analysis of B and CHP configurations for on-farm anaerobic digestion based on a herd of 185 dairy cows. The results for each cell indicate a change in abatement cost, NPV and annual GHG emissions with a ± 10% alteration in the parameter considered (e.g., SSRH, CAPEX or feedstock cost).

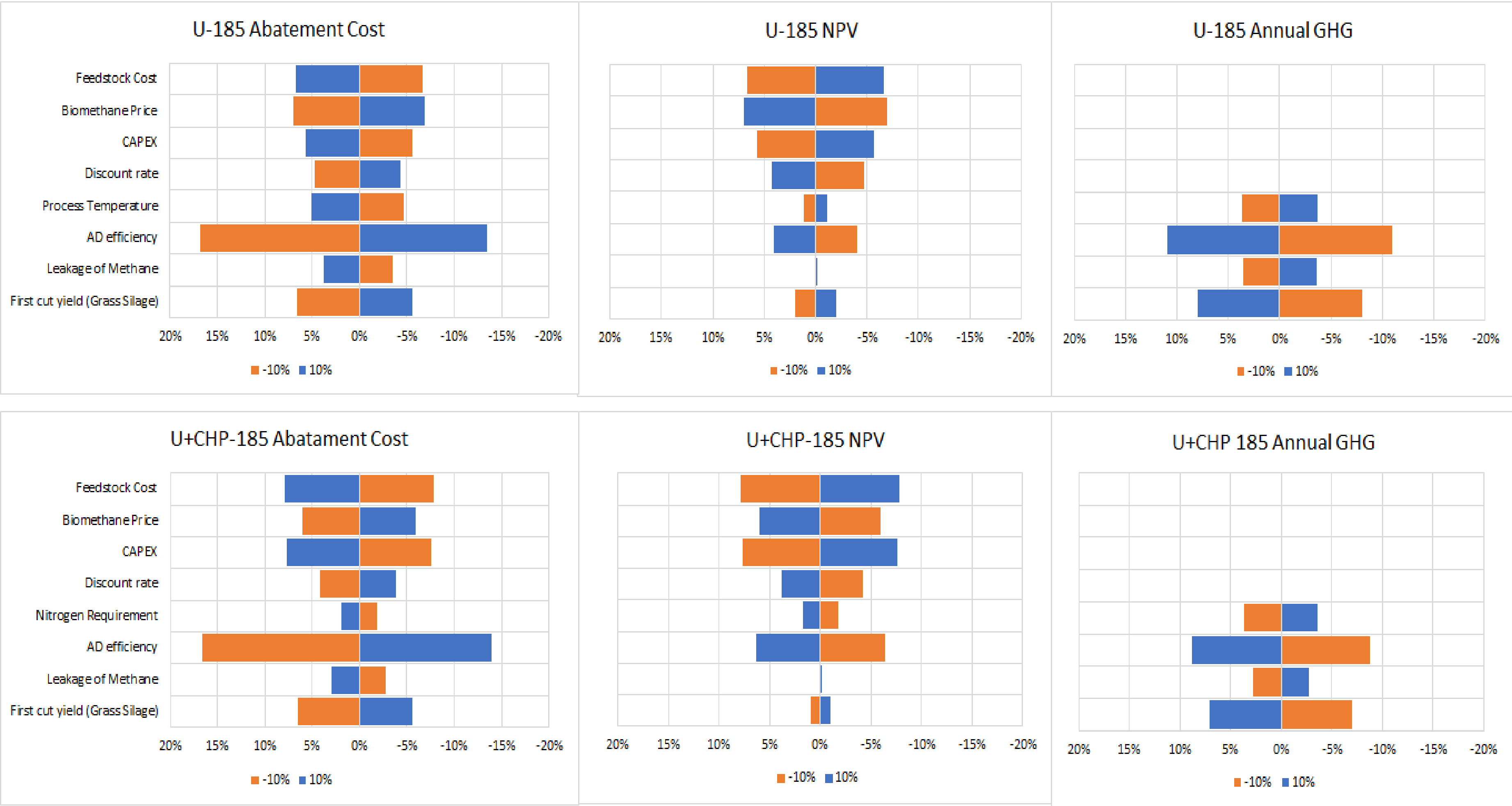

Figure 5-6 Results of the sensitivity analysis of U and U+CHP configurations for on-farm anaerobic digestion based on a herd of 185 dairy cows. The results for each cell indicate a change in abatement cost, NPV and annual GHG emissions with a ± 10% alteration in the parameter considered (e.g., SSRH, CAPEX or feedstock cost).

5.3.3 Uncertainty analysis

From the original 24 variables assessed in the sensitivity analysis, the most sensitive variables that affected the output variables across the configurations were selected for a total of 12 variables. This included the sensitive input variables that had an effect above 5% on the output variables identified for each of the configurations. Based on the relevant information available, probability distributions (Triangular and Uniform) were assigned to each of the 12 input variables.

With respect to the farm conditions, two variables were modelled: the yield of grass silage from the first cut and the synthetic fertiliser required for its cultivation. In the co-digestion of grass silage and slurry, it has been found that an increase in the portion of grass silage leads to an increase in plant profitability as there is an increase in overall methane yield (15). However, to accommodate higher amounts of grass silage, an increase in synthetic fertiliser (N) is required (8). The grass yield (tDM ha^{-1}) can vary depending on the soil type, climate location, and application rate of N (kg N ha^{-1}). For the uncertainty analysis a triangular distribution based on lower, median, and upper values of grass yield as shown in Table 5-8, considering different values depending on the time of harvest of the first cut of grass for silage production. To model the amount of synthetic fertiliser required for the cultivation of grass silage, a triangular distribution was also selected. The upper value was based on the maximum allowed amount of synthetic fertiliser set by the Good Agricultural Practice (GAP) directive (46). Consequently, the low value was estimated considering a reduction of 125 kg N a^{-1} from the requirement of synthetic fertiliser from the base case scenario (185 kg N ha^{-1}). This reduction was assumed by including white clover in a multi-species sward with perennial ryegrass in the field. White clover can fix nitrogen from the atmosphere into the field, thus decreasing the amount of synthetic fertiliser needed (14).

In terms of the operational parameters of the AD process, three variables were modelled: the efficiency of the AD process, the AD process temperature, and methane leakage from the process. A uniform distribution was selected for the AD process efficiency as it can be affected by a variety of characteristics such as pH, solids concentration (both dry and volatile), oxygen demand and other methanogenic inhibitors (50). For feedstocks such as animal slurries, with high nitrogen content, one of the most common causes of process inhibition is the accumulation of ammonia that can lead to a significant reduction in methane production: a drop of 50% in process efficiency was considered as the lower limit in the uncertainty analysis (76). In contrast, the integration of novel technologies such as microbial electrolysis cells (MEC) to the digester can enhance process stability and furthermore has been shown to increase methane production by 46%; thus, the upper limit value in the uncertainty analysis was set accordingly (74). Finally, for the process temperature and leakage of methane a uniform distribution with a variation of ± 10% from the base case scenarios values was assumed for the upper and lower values. Temperature was assumed to have a direct impact on the thermal demand, while methane leakage influenced the overall biogas production. It is assumed that no biological impact (causing alteration in biogas production) resulted from changes in temperature as the range of temperature was within the mesophilic range (77,78).

For the economic assumptions, seven variables were considered: revenues generated from support schemes (SSRH and RESS); selling prices of energy produced (heat and biomethane); the feedstock cost associated with grass silage; the discount rate applied; and the CAPEX of the systems. The price of feedstock has previously been shown to be a variable that had a significant impact on the financial performance of all configurations as per Figure 5-3 (15). To account for uncertainty in the production cost of grass silage, a triangular distribution was selected for the model. If production prices for grass silage increase in 2023, similar to the trend observed from 2021 to 2022, it is possible to assume an increase of 33% on the current price for grass silage (rising from 43 € t^{-1} to 57 € t^{-1}) which was considered for the upper value of the distribution (14). In contrast, under favourable conditions such as freeing lands from grazing to allow additional silage production or reducing the amount of synthetic fertiliser required, it is possible that production costs may decrease. A lower value of 32 € t^{-1}, which is equivalent to a price from 2015 was assumed for the lower value (79,80).

A triangular distribution was selected to model the selling price of the energy produced (heat and biomethane). The price of heat was modelled based on district heating prices, which depend on current gas prices, seasonality, and tariff schemes. The upper value assumed a low tariff scheme during a period with high seasonal demand, resulting in an increased selling price (Table 5-10). On the other hand, the lower value considered a reduced selling price, due an increase in gas prices during a period of low seasonal demand, as shown in Table 5-10 (68,81). The biomethane selling price range was derived from a previous study that evaluated such prices in Ireland, accounting for both lower and upper ranges with the exclusion and inclusion of incentives to produce biomethane (Table 5-10) (31).

Finally, a uniform distribution was selected for the support schemes (SSRH and RESS), the discount rate and the CAPEX. For the support schemes the base case scenario values were used for the lower values based on the current market conditions, with the expectation of rate increases in the future for these schemes. For the discount rate and CAPEX, the base case scenarios values were used as the upper values, as an expectation of increased investments in renewable energies in Ireland, which could reduce overall costs. For the SSRH, a higher value for the upper range was considered as it is likely that there will need to be an increase in the SSRH tariff to stimulate the market; a rate was chosen equivalent to the UK Renewable Heat Incentive (RHI) rate of 68.15 € MWh^{-1} (5.62 p£ kWh^{-1}) (82). For the RESS, the upper value was based on the increase in the support scheme from the first to the second auction carried out by EIRGRID, with a rate of 97.87 € MWh^{-1} (83). As for the discount rate, a lower value of 5% was considered, anticipating an increase in investment in renewable energies across Ireland (63). Lastly, for the CAPEX, for the lower value, the inclusion of state support in the form of a capital grant of up to 50% to fund part of the capital expenses was considered (84).

Table 5-20 Model Input Parameters for the Monte Carlo Simulation.

Model Input Parameters			
Farm Condition	**Distribution Type**	**Values**	**Source**
First Cut Yield (GS) [tDM ha^{-1}]	Triangular [a]	High: 11 Median: 7 Low: 5.9	(46)
Synthetic Fertiliser (N requirement) [kg N ha^{-1}]	Triangular [a]	High: 250 Median: 185 Low: 60	(14,46)
Process Condition			
AD efficiency [%]	Uniform [b]	High: 146 Low: 50	(74,76)
Process Temperature [ºC]	Uniform [b]	High: 44 Low: 36	Assumed, based on a +/- 10% variation of the base case value
Leakage of methane [%]	Uniform [b]	High: 2.2 Low: 1.8	Assumed, based on a +/- 10% variation of the base case value
Economic Assumptions			
SSRH [€ MWh^{-1}]	Uniform [b]	High: 68.15 Low: 29.05	(82,85)
RESS [€ MWh^{-1}]	Uniform [b]	High: 97.87 Low: 74.08	(67,83)
Heat selling price [€ MWh^{-1}]	Triangular [a]	High:87 Median:60 Low: 50	(68,81)
Biomethane Price [€ MWh^{-1}]	Triangular [a]	High: 100 Median: 53.7 Low: 40	(31)
CAPEX [€]	Uniform [b]	High: Base Case Value Low: -50%	(84)
Discount Rate [%]	Uniform [b]	High: 10 Low: 5	(63)
Feedstock Cost [€ t^{-1}]	Triangular [a]	High:57 Median:43 Low:32	(14,80,86)

[a] For triangular distributions: High= maximum bound, Median= most likely value, Low= minimum bond
[b] For uniform distributions: High= maximum bound, Low = minimum bound
[C]GS: Grass Silage

5.3.4 Probabilistic distribution of the financial viability of the systems

A total of 10,000 simulations were conducted to assess the potential economic outputs (NPV) of the scenarios based on their different biogas-end use configurations and varying herd sizes. Figure 5-5 provides a summary of the results from the Monte Carlos Simulation for the scenarios with a herd size of 185 for the NPV. Based on the results of the uncertainty assessment, the scenarios with the B and CHP configuration remained financially viable with an NPV greater than zero in 74% of the cases for the B configuration, and 55% for the CHP configuration. In contrast, the scenarios with the U and U+CHP configuration configurations were mostly not financially viable with negative NPV based on the results for the simulations. Only 1.5% of the simulations had a positive NPV for the U+CHP configuration at a herd size of 185. The profitability of the configurations followed a similar trend across the scenarios with different herd sizes (100, 60, and 40), with a reduction in profitability for the B and CHP configurations, due to the economies of scale. Detailed results of the probabilistic distributions of the herd sizes of 100, 60 and 40 can be found in Appendix C.4.

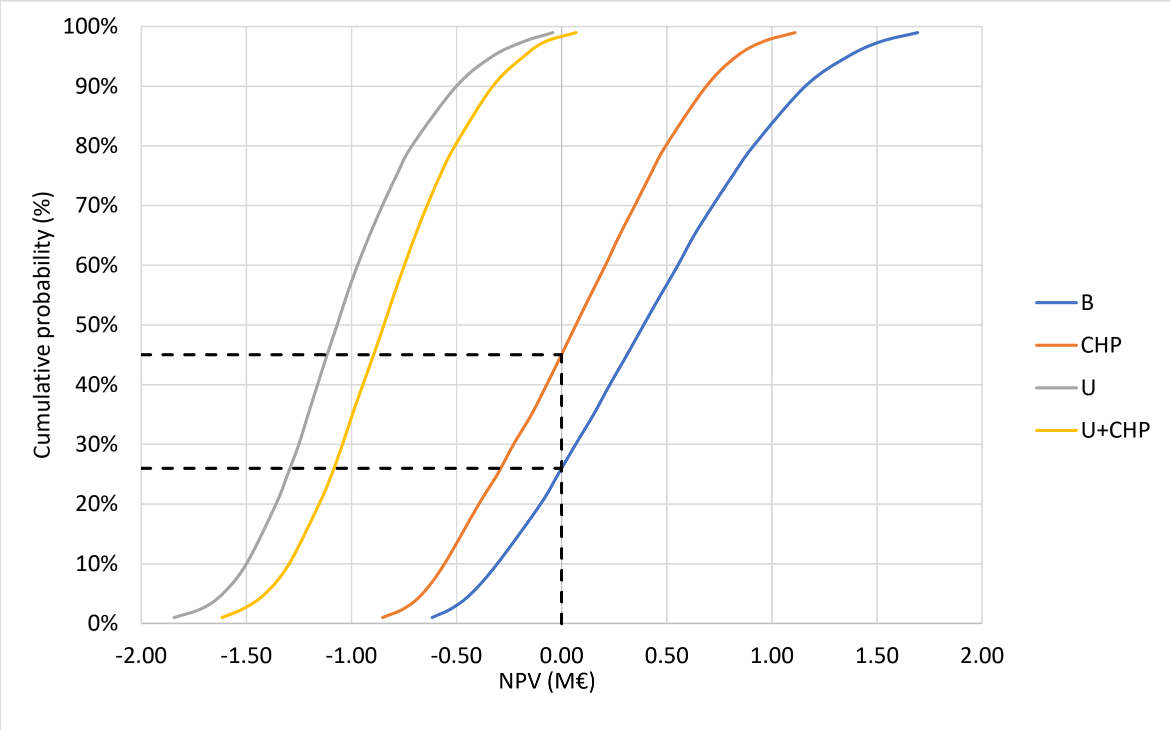

Figure 5-7 Cumulative distribution function of the Net Present Value for the 4 biogas-end use configurations for a herd size of 185.

5.3.5 Results of the uncertainty analysis for abatement cost and potential

With the simulations results, 16 abatement probability charts were developed that denote different percentages of the simulation results for the abatement cost and abatement potential for each on-farm AD scenario. Figure 5-6 shows the results of the probability ranges for the abatement cost and potential for scenarios with a herd size of 185, based on the four biogas end-use configurations. Each colour of the chart delimits the probability of a certain range of abatement cost and potential to occur based on the results of the simulation (10,000 iterations). The ranges are delimited to represent a share of the simulations results based on the probability of a result occurring within that range from 100% probability (yellow) decreasing to a 20% probability (blue).

Simulation results showed that the CHP-185 scenario had the lowest abatement cost range with a low slope gradient as seen in Figure 5-6. There was a 75% probability that the abatement cost for this scenario would range between -120 to 140 € tCO_{2eq}^{-1}, with a corresponding abatement potential range between 3,500 to 7,700 tCO_{2eq}. In contrast, the U-185 displayed the highest probability of having a high dispersion range of abatement costs with a considerable slope gradient (Figure 5.6), from 80 to 600 € tCO_{2eq}^{-1}, while accounting for a more restricted abatement potential range of 2,400 to 5,600 tCO_{2eq}.

With the inclusion of a CHP unit, the U+CHP-185 scenario led to a reduction in the abatement cost range for upgrading, narrowing it to 40 to 400 € tCO_{2eq}^{-1}. Simultaneously, the scenario's abatement potential range broadened to 3,100 to 6,500 tCO_{2eq} compared to the U-185 scenario. The B-185 scenario exhibited the highest likelihood of yielding a negative abatement cost, with a probability of 75% of encompassing a range between -200 to 100 € tCO_{2eq}^{-1}, with an abatement potential range of 3,000 to 6,600 tCO_{2eq}. This scenario displayed the highest probability of achieving cost-effective GHG emissions reduction for on-farm AD systems. The trend of uncertainty remained consistent across the different farm sizes (100, 60 and 40 herd size) with an increase in the range of abatement cost and a reduction in the abatement potential in smaller farm sizes as result of diseconomies of scale. The probability charts of the other farm sizes can be found in Appendix C.5.

Table 5-11 and Table 5-12 summarise the results from the statistical differences in the ranges of abatement cost and potential at different probabilities for the scenarios with a herd size of 185. Upon analysing the results, the interquartile range of the abatement cost for the scenarios with the B and CHP configurations remained between -144 to 75 € tCO_{2eq}^{-1} with a corresponding abatement potential between 3,578 to 6,466 tCO_{2eq} respectively, establishing a 50% probability of achieving low abatement costs for the configurations. This is further reinforced with both median values being negative, highlighting a 50% probability associated with the abatement cost being negative for both scenarios (Table 5-11). Furthermore, the scenario with the CHP configuration proved to have the lowest associated uncertainty, as it has the closest standard deviation relative to the mean abatement cost of the scenario. This highlights that the CHP scenario had the lowest dispersion among the probability distributions for abatement cost.

In contrast, the scenarios that considered upgrading (U-185 and U+CHP-185), exhibited a wider interquartile range for the abatement cost between 107 to 464 € tCO_{2eq}^{-1}, indicating a 50% probability of the scenarios of having high abatement costs. In particular, the U-185 scenario demonstrated the highest associated uncertainty as it exhibited the highest standard deviation relative to the mean across all scenarios. This can be noticed with the wider dispersion in the range the abatement cost had at different probabilities intervals as shown in Table 5-11.

In terms of the *post hoc* outcomes, it was found that all scenarios showed significant differences in terms of abatement cost (Table 5-13). Meanwhile, for the abatement potential (Table 5-14), only the B-185 and U+CHP-185 scenarios did not exhibit significant differences, as they achieved similar ranges of abatement potential.

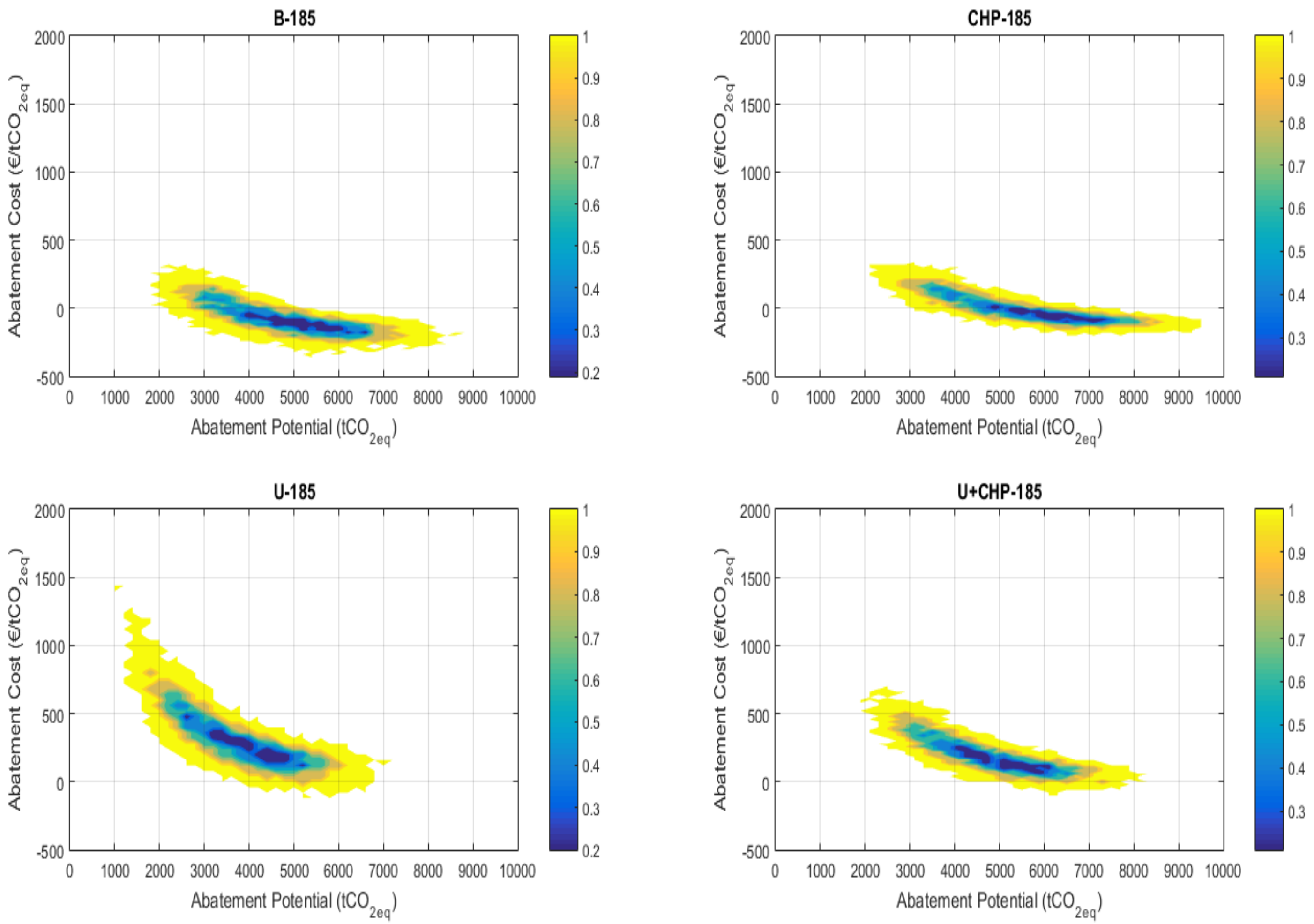

Figure 5-8 Probability chart for different confidence interval ranges of abatement cost and abatement potential of different on-farm AD systems for a heard size of 185 accounting for uncertainty. The colour band delimits the probability of a result from a 100% probability (yellow) to a 20% probability (blue) of the scenario to achieve the delimited range of abatement cost and potential.

Table 5-21 Values for the interquartile range, median, mean, and standard deviation for different probability interval ranges of abatement cost for different biogas end-uses for a herd size of 185.

Scenarios	**Summary Statistics**		**Ranges of Abatement Cost (€ tCO_{2eq}^{-1})**		
			C.I. 25% [c]	**C.I. 75%** [c]	**C.I. 95%** [c]
B-185	IQR[a] (€ tCO_{2eq}^{-1}):	-144 to 4	-180 to -20	-200 to 100	-280 to 240
	Median (€ tCO_{2eq}^{-1}):	-83			
	Mean (€ tCO_{2eq}^{-1}):	-63			
	SD[b](€ tCO_{2eq}^{-1}):	112			
CHP-185	IQR (€ tCO_{2eq}^{-1}):	-65 to 75	-100 to 40	-120 to 140	-160 to 280
	Median (€ tCO_{2eq}^{-1}):	-13			
	Mean (€ tCO_{2eq}^{-1}):	11			
	SD (€ tCO_{2eq}^{-1}):	99			
U-185	IQR (€/tCO_{2eq}):	185 to 464	120 to 480	80 to 600	0 to 960
	Median (€ tCO_{2eq}^{-1}):	293			
	Mean (€ tCO_{2eq}^{-1}):	341			
	SD(€ tCO_{2eq}^{-1}):	214			
U+CHP-185	IQR (€ tCO_{2eq}^{-1}):	107 to 292	60 to 260	40 to 400	-20 to 560
	Median (€ tCO_{2eq}^{-1}):	293			
	Mean (€ tCO_{2eq}^{-1}):	208			
	SD (€ tCO_{2eq}^{-1}):	132			

a – Interquartile Range; b – Standard Deviation; c – Probability interval for 25%, 75% and 95% of the total values centred around the mean.

Table 5-22 Values for the interquartile range, median, mean, and standard deviation for different probability interval ranges of abatement potential for different biogas end-uses for a herd size of 185.

Scenarios	**Summary Statistics**		**Ranges of Abatement Potential (tCO_{2eq})**		
			C.I. 25% [c]	**C.I. 75%** [c]	**C.I. 95%** [c]
B-185	IQR[a] (tCO_{2eq}):	3,578 to 5,693	3,600 to 6,400	3,000 to 6,600	2,000 to 8,000
	Median (tCO_{2eq}):	4,641			
	Mean (tCO_{2eq}):	4,675			
	SD[b] (tCO_{2eq}):	1,353			
CHP-185	IQR (tCO_{2eq}):	4,125 to 6,466	4,700 to 7,300	3,500 to 7,700	2,700 to 9,100
	Median (tCO_{2eq}):	5,304			
	Mean (tCO_{2eq}):	5,343			
	SD (tCO_{2eq}):	1,504			
U-185	IQR (tCO_{2eq}):	2,688 to 4,512	2,600 to 5,200	2,400 to 5,600	1,600 to 6,200
	Median (tCO_{2eq}):	3,609			
	Mean (tCO_{2eq}):	3,628			
	SD (tCO_{2eq}):	1,158			
U+CHP-185	IQR (tCO_{2eq}):	3,665 to 5,568	3,900 to 6,100	3,100 to 6,500	2,500 to 7,700
	Median (tCO_{2eq}):	4,591			
	Mean (tCO_{2eq}):	4,643			
	SD (tCO_{2eq}):	1,229			

a – Interquartile Range; b – Standard Deviation; c – Probability interval for 25%, 75% and 95% of the total values centred around the mean.

Table 5-23 Results of the post hoc analysis for the abatement cost comparing different biogas-end use configurations for the scenarios for a herd size of 185.

Compared Scenarios		**Absolute Mean Difference (€ tCO_{2eq}^{-1})**	**Q Critical Value**	**Significant Difference**
B-185	**CHP-185**	74	5.32	Yes
B-185	**U-185**	404	5.32	Yes
B-185	**U+CHP-185**	271	5.32	Yes
CHP-185	**U-185**	330	5.32	Yes
CHP-185	**U+CHP-185**	197	5.32	Yes
U-185	U+CHP-185	133	5.32	Yes

Table 5-24 Results of the post hoc analysis for the abatement potential comparing different biogas-end use configurations for the scenarios for a herd size of 185.

Compared Scenarios		**Absolute Mean Difference (tCO_{2eq})**	**Q Critical Value**	**Significant Difference**
B-185	**CHP-185**	668	47.87	Yes
B-185	**U-185**	1047	47.87	Yes
B-185	**U+CHP-185**	32	47.87	No
CHP-185	**U-185**	1715	47.87	Yes
CHP-185	**U+CHP-185**	700	47.87	Yes
U-185	**U+CHP-185**	1015	47.87	Yes

5.4 Discussion

From the results of the base case scenarios, the scenarios that considered the B and CHP configuration had the best overall performance of abatement cost across the different farm sizes. Furthermore, the overall greenhouse gas (GHG) mitigation of the systems increased proportionally with farm size. This can be attributed to a higher amount of feedstock treated in the AD process, resulting in greater energy outputs that translated into more emissions displacement from energy (electricity and heat) and fuel (diesel) replacement. Overall, the scenarios employing a CHP configuration achieved higher net GHG mitigation across the different farm sizes, as the scenarios accounted for both emissions savings from electricity and heat displacement. On the other hand, for the scenarios that considered biogas upgrading (U and U+CHP), no incentives were considered within the base case scenario's economic assumptions. These configurations relied solely on biomethane sales and reduced synthetic fertiliser costs due to biofertiliser (digestate) use. Consequently, these scenarios exhibited a lower financial viability compared to the B and CHP configurations.

Two different schemes could be considered as incentives to increase the financial viability of the production of biomethane. Under the Renewable Transport Fuel Obligation scheme, Ireland requires transport fuel suppliers to ensure that 15% of the fuel volume on the market is sourced from renewable fuels (87). Producers of biomethane can apply to receive three Biofuel Obligation Certificates (BOC) under this scheme, which trade within a range of 0.39 to 1.08 € m_n^{-3} of methane, equivalent to 38 to 106 € MWh^{-1}, although this range can fluctuate based on market forces (88,89). The SSRH scheme for renewable heat could also be applied (29.5 € MWh^{-1}), although biomethane grid injection is still under consideration to be included in subsequent phases of the scheme (69). For the base case scenarios that considered the upgrading configuration (UPG-185 to UPG-40), to reach an abatement cost within the carbon tax set for Ireland of 80 € tCO_2^{-1} (72), an incentive between 68 to 116 € MWh^{-1} would be required. Under the SSRH scheme, this would be unrealistic as it would require at least an increase of 130% in the current scheme. However, such an incentive would be feasible for systems with an increased herd size if Biofuel Obligation Certificate prices are considered. Although, these certificates are dependent on the fuel production of the applicant meeting the sustainability criteria set by the recast RED II directive (87).

For all the scenarios, the AD efficiency (defined here as commercial efficiency as compared to lab efficiency) proved to be an essential variable to consider for optimisation, as it affected both the financial and environmental performance of the on-farm AD systems, and thus directly impacted the abatement cost. The financial performance of scenarios with the B and CHP configuration were more sensitive to changes to the efficiency of the process as highlighted in section 5.3.2. Notably, scenarios with the B configuration exhibited high sensitivity, primarily because their baseline values were close to zero. This implies that a 10% increase in input variables would result in a relatively higher percentage change compared to the baseline value. Previous research carried out for co-digestion of grass silage and slurry also found that the operational efficiency of the AD facility is essential to consider, as it has a direct impact on biomethane production cost (15).

Conversely, in the scenarios that considered an upgrading configuration (U and U+CHP) the efficiency in the process had an increased impact on the abatement achieved by the scenarios as highlighted in section 5.3.2. Decreased efficiency translates into lower methane yields, leading to reduced biomethane production and diminished abatement potential from emissions savings due to energy displacement. The upgrading process generated more emissions than the other configurations, as the energy requirements are sourced from electricity and gas from the grid. An increase in efficiency, can increase the emissions from leakage during biogas production, which can represent between 43 to 46% of the total emissions generated in the upgrading process (25).

Based on the outcomes of the simulations, the scenarios that considered the B and CHP configurations for biogas end-use showed the best financial viability for implementing on-farm AD systems in Ireland, given the assumptions used in this assessment. The robust economic performance of the scenarios illustrated that such systems do not currently require additional incentivisation schemes. This is based on the assumption there will be a continuous increase in the level of support from the current schemes (SSRH and RESS) year on year, as a response to the increased uncertainty in energy prices due to recent geo-political events (19) and the need to increase levels of decarbonisation to reach Ireland's Climate Action mandated targets.

As part of the assumptions for the uncertainty analysis, an increase in the biomethane selling price and a reduction in capital cost through capital grants were considered to improve the financial viability of the scenarios that considered the upgrading configuration. However, the results from the cumulative probability distributions of financial viability, indicated that most of the systems with an upgrading configuration (U and U+CHP) remained financially unviable. Among the scenarios, only the U+CHP-185 scenario demonstrated results with a positive NPV in just 1.54% of the total simulations. Small-scale biogas upgrading can be commercially challenging, particularly due to the high cost of the upgrading technologies for low biogas flow rates, as these systems require equipment used for larger capacity systems, thus increasing their cost per unit biogas upgraded (60). Based on these results of the simulations, the implementation of incentives will be crucial to make the biogas market accessible for farmers as small-scale biomethane producers. This could also be achieved by considering the use of mobile upgrading systems which can be obtained through farming cooperatives to further reduce the capital cost of the systems (90), or by adding additional revenue streams by co-producing biomethane with other high-value products such as micro-algae (a super food) associated with photosynthetic microalgal upgrading (91,92).

Finally, based on the results of the simulations of the abatement potential, the scenarios considering the upgrading configuration (U) had a high probability of achieving lower emissions reductions compared to the other configuration. This can impact directly on the sustainability of the systems, so integrating a CHP unit could mitigate emissions and enhance the sustainability of the upgrading configuration by displacing emissions associated with fossil fuels used during the production process. This is evident in the simulation results for the U+CHP-185 scenario, which exhibited an increased probability of achieving a higher emissions reduction range compared to the U-185 scenario results. This scenario reduced the overall abatement cost of the configuration with a 75% probability of increasing the range of abatement potential by 29% for the lower bound and by 16% for the upper bound as shown in Table 5-12. This approach improves stakeholders' comprehension of uncertainty related to specific on-farm AD systems, leading to more informed decision-making.

It also aids in identifying economically viable options and necessary incentives for successful on-farm AD implementation. To allow small-scale on-farm scenarios that consider upgrading to be eligible for incentivisation it might be required to include a CHP unit to meet sustainability criteria such as the one required for the Renewable Transport Fuel Obligation scheme.

5.5 Conclusion

Three objectives were set at the start of the study and the key findings for each can be found below:

• Identify through a sensitivity analysis the main financial and environmental variables affecting the abatement cost for on-farm AD systems.

It was found that one of the main variables that influences the abatement cost was the efficiency of the AD process (defined as the specific methane yield achieved in the commercial process as compared to that achieved in the lab), as this directly affected the financial and environmental performance of all scenarios. In particular, the scenarios with the boiler configuration had a high sensitivity to this variable, as shown in the B-185 scenario where a 10% increase in efficiency reduced the abatement cost by almost 450%. This variable could prove essential to consider for optimisation to obtain a low abatement cost consistently. The top 5 input variables that had the greatest impact on the abatement cost across all systems include: the feedstock cost; grass silage yield; selling prices of energy (heat and biomethane); revenues considered in the support schemes (SSRH and RESS); and the CAPEX of the system.

• Evaluate the potential ranges of abatement cost and abatement potential for different biogas end-uses at different farm scales through Monte Carlo analysis.

The simulation results indicated that the trend of uncertainty across the scenarios remained consistent with an increase in the range of abatement cost and a reduction in the abatement potential in smaller farm sizes as result of diseconomies of scale. The scenarios that had the lowest abatement cost range dispersion, were the scenarios that considered the CHP configuration. In particular, the results from the CHP-185 scenario had a 75% probability of achieving an abatement cost range between -140 to 200 € tCO_{2eq}^{-1}, with an abatement potential range of 3,500 to 7,700 tCO_{2eq}^{-1}. The scenarios that considered the upgrading configuration had the highest ranges of abatement cost, due the increased uncertainty making them a high-cost abatement solution for small scale on-farm AD systems based on the assumptions in this work.

• Assess the results of the Monte Carlo analysis based on the overall uncertainty associated with the abatement cost and abatement potential to identify if additional incentives are required for on-farm AD systems.

Integrating uncertainty analysis in the assessment of abatement cost and abatement potential can provide a more robust evaluation to assess the financial and environmental performance of a biogas project. By providing a range of potential abatement costs and abatement potentials, researchers can gain insights into the system configurations that yield the best results for on-farm AD. Moreover, the range of results allows decision makers to identify whether increased incentives or additional schemes are necessary.

Based on the overall results, the scenarios involving the boiler and CHP configurations for biogas end-use currently do not require additional incentives, considering the assumptions made in this study. In contrast, the scenarios with the upgrading configuration proved to be not financially viable with high uncertainty in the abatement cost range. Based on the baseline assumptions for the upgrading scenarios, an incentive in the range of 68 to 116 € MWh^{-1} would be required to reach abatement cost within the carbon tax set for Ireland. However, to make small-scale scenarios considering upgrading eligible for incentivisation, it may be necessary to incorporate a CHP unit to meet the REDII sustainability criteria mandated by schemes like the Biofuel Obligation Certificates. This could increase the abatement potential range, as demonstrated in the results scenarios with the U+CHP configuration.

References

1. Government of Ireland. Climate Action Plan 2023 [Internet]. 2023 [cited 2023 May 2]. Available from: https://www.gov.ie/en/publication/7bd8c-climate-action-plan-2023/

2. O'connor S, Ehimen E, Pillai SC, Power N, Lyons GA, Bartlett J. An Investigation of the Potential Adoption of Anaerobic Digestion for Energy Production in Irish Farms. Environments 2021, Vol 8, Page 8 [Internet]. 2021 Jan 27 [cited 2022 Apr 21];8(2):8. Available from: https://www.mdpi.com/2076-3298/8/2/8/htm

3. European Commission. REPowerEU: affordable, secure and sustainable energy for Europe [Internet]. 2022 [cited 2023 May 30]. Available from: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en

4. Sulewski P, Ignaciuk W, Szymańska M, Wąs A. Development of the Biomethane Market in Europe. Energies 2023, Vol 16, Page 2001 [Internet]. 2023 Feb 17 [cited 2023 May 31];16(4):2001. Available from: https://www.mdpi.com/1996-1073/16/4/2001/htm

5. IEA Bioenergy Task 37. Country Report Summaries 2021 [Internet]. 2022 [cited 2023 May 31]. Available from: https://task37.ieabioenergy.com/country-reports

6. Wall DM, O'Kiely P, Murphy JD. The potential for biomethane from grass and slurry to satisfy renewable energy targets. Bioresour Technol [Internet]. 2013 [cited 2022 Apr 21];149:425–31. Available from: https://pubmed.ncbi.nlm.nih.gov/24135566/

7. O'Shea R, Wall D, Kilgallon I, Murphy JD. Assessment of the impact of incentives and of scale on the build order and location of biomethane facilities and the feedstock they utilise. Appl Energy. 2016 Nov 15;182:394–408.

8. Beausang C, McDonnell K, Murphy F. Assessing the environmental sustainability of grass silage and cattle slurry for biogas production. J Clean Prod. 2021 May 20;298:126838.

9. CSO. Livestock Survey December 2022 [Internet]. 2022 [cited 2023 Jul 6]. Available from: https://www.cso.ie/en/releasesandpublications/ep/p-lsd/livestocksurveydecember2022/

10. McEniry J, Crosson P, Finneran E. JSTOR. 2013 [cited 2022 Nov 16]. How much grassland biomass is available in Ireland in excess of livestock requirements? Available from: https://www.jstor.org/stable/23631018

11. Bedoić R, Čuček L, Ćosić B, Krajnc D, Smoljanić G, Kravanja Z, et al. Green biomass to biogas – A study on anaerobic digestion of residue grass. J Clean Prod. 2019 Mar 10;213:700–9.

12. Nilsson J, Sundberg C, Tidåker P, Hansson PA. Regional variation in climate impact of grass-based biogas production: A Swedish case study. J Clean Prod. 2020 Dec 1;275:122778.

13. Boscaro D, Pezzuolo A, Sartori L, Marinello F, Mattioli A, Bolzonella D, et al. Evaluation of the energy and greenhouse gases impacts of grass harvested on riverbanks for feeding anaerobic digestion plants. J Clean Prod. 2018 Jan 20;172:4099–109.

14. Teagasc. The cost of producing home-grown feeds on Irish farms [Internet]. 2022 [cited 2022 Sep 20]. Available from: https://www.teagasc.ie/animals/beef/grange/beef2022-open-day/the-cost-of-producing-home-grown-feeds--/

15. Himanshu H, Murphy JD, Lenehan JJ, O'Kiely P. Impacts of characteristics of grass silage and cattle slurry feedstocks on the cost of methane production. Biofuels, Bioproducts and Biorefining [Internet]. 2019 Jan 1 [cited 2023 Jan 17];13(1):129–39. Available from: https://onlinelibrary-wiley-com.ucc.idm.oclc.org/doi/full/10.1002/bbb.1947

16. IEA Bioenergy Task 37. Country Report Summaries 2019 [Internet]. 2020 [cited 2022 Apr 21]. Available from: https://task37.ieabioenergy.com/country-reports.html

17. KPMG, Devenish, Gas Networks Ireland. Sustainability of Biomethane Production in Ireland Exploring how Ireland can deliver a sustainable, agriculture-

led biomethane industry [Internet]. 2021 [cited 2022 Jul 21]. Available from: https://www.gasnetworks.ie/biomethane-sustainability-report-2021.pdf

18. Gas Network Ireland. Investors ready for Irish biomethane facilities as demand for green energy soars [Internet]. 2022 [cited 2023 Jun 1]. Available from: https://www.gasnetworks.ie/corporate/news/active-news-articles/irish-biomethane-investment/

19. Kuik F, Adolfsen JF, Meyler A, Lis E. European Central Bank. 2022 [cited 2023 Jun 4]. Energy price developments in and out of the COVID-19 pandemic – from commodity prices to consumer prices. Available from: https://www.ecb.europa.eu/pub/economic-bulletin/articles/2022/html/ecb.ebart202204_01~7b32d31b29.en.html

20. European Commission. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) [Internet]. 2018 [cited 2022 Jul 21]. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC

21. Murthy GS. Life-Cycle Assessment. In: Bioenergy : principles and applications. Wiley-Blackwell; 2016. p. 521–43.

22. Vogt-Schilb A, Meunier G, Hallegatte S. When starting with the most expensive option makes sense: Optimal timing, cost and sectoral allocation of abatement investment. J Environ Econ Manage. 2018 Mar 1;88:210–33.

23. Government of Ireland. Climate Action Plan 2019 [Internet]. 2019 [cited 2022 Jul 13]. Available from: https://www.gov.ie/en/publication/ccb2e0-the-climate-action-plan-2019/

24. Lanigan GJ, Hanrahan K, Richards KG, Lanigan G, Black K, Donnellan T, et al. MACC 2023: An Updated Analysis of the Greenhouse Gas Abatement Potential of the Irish Agriculture and Land-Use Sectors between 2021 and 2030 [Internet]. Teagasc. 2023 [cited 2023 Aug 2]. Available from: https://www.teagasc.ie/media/website/environment/climate-action/climate-centre/MACC-2023.pdf

25. Diaz Huerta J, Bose A, Wall DM, Murphy JD, O'Shea R. Assessing the cost variability of emissions abatement in small-scale on-farm anaerobic digestion. DeCarbon [Internet]. 2023 Jun 1 [cited 2023 Jun 9];1:100008. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2949881323000082

26. Tolessa A, Goosen NJ, Louw TM. Probabilistic simulation of biogas production from anaerobic co-digestion using Anaerobic Digestion Model No. 1: A case study on agricultural residue. Biochem Eng J. 2023 Mar 1;192:108810.

27. Tolessa A, Louw TM, Goosen NJ. Probabilistic techno-economic assessment of anaerobic digestion predicts economic benefits to smallholder farmers with quantifiable certainty. Waste Management. 2022 Feb 1;138:8–18.

28. Dennehy C, Lawlor PG, Gardiner GE, Jiang Y, Shalloo L, Zhan X. Stochastic modelling of the economic viability of on-farm co-digestion of pig manure and food waste in Ireland. Appl Energy. 2017 Nov 1;205:1528–37.

29. Peng BB, Xu JH, Fan Y. Modeling uncertainty in estimation of carbon dioxide abatement costs of energy-saving technologies for passenger cars in China. Energy Policy. 2018 Feb;113:306–19.

30. Sjöstrand K, Lindhe A, Söderqvist T, Dahlqvist P, Rosén L. Marginal Abatement Cost Curves for Water Scarcity Mitigation under Uncertainty. Water Resources Management. 2019 Sep 31;33(12):4335–49.

31. Bose A, O'Shea R, Lin R, Long A, Rajendran K, Wall D, et al. The marginal abatement cost of co-producing biomethane, food and biofertiliser in a circular economy system. Renewable and Sustainable Energy Reviews [Internet]. 2022 Nov 1 [cited 2022 Nov 1];169:112946. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1364032122008279

32. Lumivero. @RISK | Risk Analysis using Monte Carlo Simulation in Excel | Palisade [Internet]. 2023 [cited 2023 Jun 7]. Available from: https://www.palisade.com/risk/

33. Harris A, Soban D, Smyth BM, Best R. Assessing life cycle impacts and the risk and uncertainty of alternative bus technologies. Renewable and Sustainable Energy Reviews. 2018 Dec 1;97:569–79.

34. Benalcazar P, Komorowska A. Prospects of green hydrogen in Poland: A techno-economic analysis using a Monte Carlo approach. Int J Hydrogen Energy. 2022 Jan 29;47(9):5779–96.

35. Dillon E, Donnellan T, Moran B, Lennon J. Teagasc National Farm Survey 2020 Results Rural Economy Development Programme Acknowledgements. 2021;

36. Central Statistics Office. Farm Structure - CSO [Internet]. 2021 [cited 2022 Sep 20]. Available from: https://www.cso.ie/en/releasesandpublications/ep/p-coa/censusofagriculture2020-preliminaryresults/farmstructure/

37. Hennessy T, Buckley C, Cushion M. teagasc. 2011 [cited 2022 Mar 10]. National farm survey of manure application and storage practices on Irish farms. Available from: https://www.teagasc.ie/media/website/publications/2011/TeagascNationalFarmSurveyOfManureApplication.pdf

38. Buckley C, Moran B, Donnellan T. Teagasc National Farm Survey A Report on Bovine Manure Management, Application and Storage Practices in Ireland. 2020;

39. Teagasc. Fertilising 2 nd Cut Grass Silage [Internet]. 2018 [cited 2022 Aug 4]. Available from: https://www.teagasc.ie/media/website/crops/soil-and-soil-fertility/2nd-Cut-Grass-Silage-N,-P-K-Req.pdf

40. Teagasc. Grassland - Grass Silage and Hay [Internet]. 2022 [cited 2022 Sep 20]. Available from: https://www.teagasc.ie/crops/soil--soil-fertility/grassland/grass-silage-and-hay/

41. Allen E, Wall DM, Herrmann C, Murphy JD. A detailed assessment of resource of biomethane from first, second and third generation substrates. Renew Energy. 2016 Mar 1;87:656–65.

42. Murphy JD, Power NM. An argument for using biomethane generated from grass as a biofuel in Ireland. Biomass Bioenergy. 2009 Mar 1;33(3):504–12.

43. Meehan P, Burke B, Doyle D, Barth S, Finnan J. Exploring the potential of grass feedstock from marginal land in Ireland: Does marginal mean lower yield? Biomass Bioenergy. 2017 Dec 1;107:361–9.

44. Smyth BM, Murphy JD, O'Brien CM. What is the energy balance of grass biomethane in Ireland and other temperate northern European climates? Renewable and Sustainable Energy Reviews. 2009 Dec 1;13(9):2349–60.

45. Holen NM, Brereton AJ. Vol. 41, Irish Journal of Agricultural and Food Research. 2022 [cited 2022 Jun 14]. p. 213–26 An Assessment of the Potential Impact of Climate Change on Grass Yield in Ireland over the Next 100 Years on JSTOR. Available from: https://www.jstor.org/stable/25562465?seq=1

46. Ruelle E, Delaby L, Shalloo L, O'Donovan M, Hennessy D, Egan M, et al. Modelling the effects of stocking rate, soil type, agroclimate location and nitrogen input on the grass DM yield and forage self-sufficiency of Irish grass-based dairy production systems. J Agric Sci [Internet]. 2022 Jun 8 [cited 2023 Jun 15];160(3–4):235–49. Available from: https://www.cambridge.org/core/journals/journal-of-agricultural-science/article/modelling-the-effects-of-stocking-rate-soil-type-agroclimate-location-and-nitrogen-input-on-the-grass-dm-yield-and-forage-selfsufficiency-of-irish-grassbased-dairy-production-systems/1AB3BD3A5B8DD3E42F33FD9FFABFCC4D

47. Fjørtoft K, Morken J, Hanssen JF, Briseid T. Methane production and energy evaluation of a farm scaled biogas plant in cold climate area. Bioresour Technol. 2014 Oct 1;169:72–9.

48. Ahlberg-Eliasson K, Nadeau E, Levén L, Schnürer A. Production efficiency of Swedish farm-scale biogas plants. Biomass Bioenergy. 2017 Feb 1;97:27–37.

49. Van Stappen F, Mathot M, Decruyenaere V, Loriers A, Delcour A, Planchon V, et al. Consequential environmental life cycle assessment of a farm-scale biogas plant. J Environ Manage. 2016 Jun 15;175:20–32.

50. Wall DM, Allen E, Straccialini B, O'Kiely P, Murphy JD. Optimisation of digester performance with increasing organic loading rate for mono- and co-digestion of grass silage and dairy slurry. Bioresour Technol. 2014 Dec 1;173:422–8.

51. Liebetrau J, Clemens J, Cuhls C, Hafermann C. Methane emissions from biogas-producing facilities within the agricultural sector. Eng Life Sci [Internet]. 2010 [cited 2022 Dec 6];10(6):595–9. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/elsc.201000070?casa_token=McPVF

CtGSxwAAAAA:igXy_XypY3X7X3k83pDalpwCqQE6zv-c3VWymWffITc3KOto6sIOjqFcvutf-zGQdfLQIVk6zzJfqQ

52. van den Oever AEM, Cardellini G, Sels BF, Messagie M. Life cycle environmental impacts of compressed biogas production through anaerobic digestion of manure and municipal organic waste. J Clean Prod. 2021 Jul 15;306:127156.

53. ASHRAE. Handbook - Fundamentals (SI). Climatic design conditions for Cork 2009/2013/2017 [Internet]. 2017 [cited 2022 Jun 2]. Available from: http://ashrae-meteo.info/v2.0/?lat=51.841&lng=-8.491&place=%27%27&wmo=039550&si_ip=SI&ashrae_version=2017

54. Labatut RA, Angenent LT, Scott NR. Conventional mesophilic vs. thermophilic anaerobic digestion: A trade-off between performance and stability? Water Res. 2014 Apr 15;53:249–58.

55. Wu B, Lin R, O'Shea R, Deng C, Rajendran K, Murphy JD. Production of advanced fuels through integration of biological, thermo-chemical and power to gas technologies in a circular cascading bio-based system. Renewable and Sustainable Energy Reviews. 2021 Jan 1;135:110371.

56. O'Shea R, Wall DM, Kilgallon I, Browne JD, Murphy JD. Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region. Appl Energy. 2017 Feb 15;188:237–56.

57. O'Connor S, Ehimen E, Pillai SC, Black A, Tormey D, Bartlett J. Biogas production from small-scale anaerobic digestion plants on European farms. Renewable and Sustainable Energy Reviews. 2021 Apr 1;139:110580.

58. O'Connor S, Ehimen E, Pillai SC, Lyons G, Bartlett J. Economic and Environmental Analysis of Small-Scale Anaerobic Digestion Plants on Irish Dairy Farms. Energies [Internet]. 2020 Feb 3 [cited 2022 May 23];13(3):637. Available from: https://www.mdpi.com/1996-1073/13/3/637/htm

59. Villarroel-Schneider J, Mainali B, Martí-Herrero J, Malmquist A, Martin A, Alejo L. Biogas based polygeneration plant options utilizing dairy farms waste: A Bolivian case. Sustainable Energy Technologies and Assessments. 2020 Feb 1;37:100571.

60. Bauer F, Hulteberg C, Persson T, Tamm D. Biogas upgrading-Review of commercial technologies; Biogasuppgradering-Granskning av kommersiella tekniker. 2013 [cited 2022 Jun 15]; Available from: https://www.osti.gov/etdeweb/biblio/22090519

61. Rotunno P, Lanzini A, Leone P. Energy and economic analysis of a water scrubbing based biogas upgrading process for biomethane injection into the gas grid or use as transportation fuel. Renew Energy. 2017 Mar;102:417–32.

62. Statista. Ireland - Inflation rate 2027 [Internet]. 2023 [cited 2022 Sep 27]. Available from: https://www.statista.com/statistics/375229/inflation-rate-in-ireland/

63. Grant Thornton. Renewable energy discount rate survey results-2018 [Internet]. 2019 [cited 2023 Jun 14]. Available from: https://www.grantthornton.co.uk/insights/renewable-energy-discount-rate-survey/

64. de Dobbelaere A, Keulenaere B, de Mey J, Lebuf V, Meers E, Ryckaert B, et al. Small-scale anaerobic digestion : case studies in Western Europe. 2015.

65. SEAI. Commercial / Industrial Fuels 01-Jul-22 Comparison of Energy Costs [Internet]. 2022 [cited 2022 Sep 20]. Available from: www.seai.ie/data-and-insights/seai-statistics/key-publications/

66. O'Shea R, Lin R, Wall DM, Browne JD, Murphy JD. Using biogas to reduce natural gas consumption and greenhouse gas emissions at a large distillery. Appl Energy. 2020 Dec 1;279:115812.

67. EIRGRID. Renewable Electricity Support Scheme 1 RESS 1 Final Auction Results [Internet]. 2020 [cited 2022 Jul 1]. Available from: https://www.eirgridgroup.com/site-files/library/EirGrid/207158-EirGrid-Renewable-Energy-Scheme-LR5.pdf

68. Bruton T. A Guide to District Heating in Ireland [Internet]. 2016 [cited 2022 Sep 20]. Available from: https://www.seai.ie/publications/2016_RDD_79._Guide_District_Heating_Irl_-_CODEMA.pdf

69. SEAI. Support Scheme for Renewable Heat Scheme Overview [Internet]. 2019 [cited 2022 Aug 1]. Available from: https://www.seai.ie/publications/SSRH-Scheme-Details-.pdf

70. SEAI. Prices - Energy Statistics In Ireland [Internet]. 2022 [cited 2022 Aug 12]. Available from: https://www.seai.ie/data-and-insights/seai-statistics/key-statistics/prices/

71. Long A, Murphy JD. 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. 2019 Nov 1;115:109347.

72. Greenhouse gas emissions and projections | Environmental Protection Agency [Internet]. [cited 2023 Feb 2]. Available from: https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/

73. Chen Y, Liu A, Zhang Z, Hope C, Crabbe MJC. Economic losses of carbon emissions from circum-Arctic permafrost regions under RCP-SSP scenarios. Science of The Total Environment. 2019 Mar;658:1064–8.

74. Wang W, Lee DJ, Lei Z. Integrating anaerobic digestion with microbial electrolysis cell for performance enhancement: A review. Bioresour Technol. 2022 Jan 1;344:126321.

75. Ning X, Deng C, Hickey DT, Hackula A, O'Shea R, Wall DM, et al. Improving biomethane production from biochar-supplemented two-stage anaerobic digestion of on-farm feedstocks. J Clean Prod. 2023 Sep;138723.

76. Jiang Y, McAdam E, Zhang Y, Heaven S, Banks C, Longhurst P. Ammonia inhibition and toxicity in anaerobic digestion: A critical review. Journal of Water Process Engineering. 2019 Dec 1;32:100899.

77. Westerholm M, Isaksson S, Karlsson Lindsjö O, Schnürer A. Microbial community adaptability to altered temperature conditions determines the potential for process optimisation in biogas production. Appl Energy. 2018 Sep;226:838–48.

78. Chae KJ, Jang A, Yim SK, Kim IS. The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. Bioresour Technol. 2008 Jan;99(1):1–6.

79. Reidy B. Irish Examiner. 2015 [cited 2023 Jun 24]. Silage costs you at least €28-32/t. Available from: https://www.irishexaminer.com/farming/arid-20320467.html

80. Ricardo Energy & Environment. Assessment of Cost and Benefits of Biogas and Biomethane in Ireland [Internet]. 2017 [cited 2022 Aug 4]. Available from: https://www.seai.ie/publications/Assessment-of-Cost-and-Benefits-of-Biogas-and-Biomethane-in-Ireland.pdf

81. Helen. District heat prices | Helen [Internet]. 2023 [cited 2023 Jun 24]. Available from: https://www.helen.fi/en/heating-and-cooling/district-heat/district-heat-prices

82. Government of UK. Non-domestic Renewable Heat Incentive (RHI) [Internet]. 2023 [cited 2023 Jun 22]. Available from: https://www.gov.uk/non-domestic-renewable-heat-incentive

83. EIRGRID. Renewable Electricity Support Scheme 2 RESS 2 Final Auction Results. 2022;

84. Stephen R. Farmer's Journal. 2022 [cited 2023 Jun 24]. Funding the Government's €2bn biomethane ambition. Available from: https://www.farmersjournal.ie/funding-the-government-s-2bn-biomethane-ambition-725842

85. SEAI. Support Scheme for Renewable Heat [Internet]. 2023. Available from: https://www.seai.ie/business-and-public-sector/business-grants-and-supports/support-scheme-renewable-heat/

86. Teagasc. Early Turnout and Silage Costs for 2022 [Internet]. 2022 [cited 2022 Jul 1]. Available from: https://www.teagasc.ie/publications/2022/early-turnout-and-silage-costs-for-2022.php

87. NORA. RTFO [Internet]. 2023 [cited 2023 Jul 27]. Available from: https://www.nora.ie/rtfo

88. Ahern EP, Deane P, Persson T, Ó Gallachóir B, Murphy JD. A perspective on the potential role of renewable gas in a smart energy island system. Renew Energy. 2015 Jun 1;78:648–56.

89. O'Shea R, Wall D, Kilgallon I, Murphy JD. Assessment of the impact of incentives and of scale on the build order and location of biomethane facilities and the feedstock they utilise. Appl Energy. 2016 Nov 15;182:394–408.

90. Gil-Carrera L, Browne JD, Kilgallon I, Murphy JD. Feasibility study of an off-grid biomethane mobile solution for agri-waste. Appl Energy. 2019 Apr 1;239:471–81.

91. Oreggioni GD, Luberti M, Tassou SA. Agricultural greenhouse CO2 utilization in anaerobic-digestion-based biomethane production plants: A techno-economic and environmental assessment and comparison with CO2 geological storage. Appl Energy. 2019 May 15;242:1753–66.

92. Bose A, O'Shea R, Lin R, Long A, Rajendran K, Wall D, et al. Evaluation of a biomethane, food and biofertiliser polygeneration system in a circular economy system. Renewable and Sustainable Energy Reviews. 2022 Dec 1;170:112960.

6 Investigating the economic impact of novel technologies and biogas logistics on on-farm anaerobic digestion

Investigating the economic impact of novel technologies and biogas logistics on on-farm anaerobic digestion.

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Abstract:

Ireland seeks to produce 5.7 TWh of biomethane from anaerobic digestion (AD) plants to decrease dependence on fossil-derived natural gas. To achieve this goal the agricultural sector will be required to assess viable options to decarbonise while ensuring that the emissions reduction target of 25% is achieved. On-farm AD can provide a suitable opportunity for Ireland to generate biomethane while mitigating emissions from livestock production. However, previous assessments have shown that due, the elevated cost of upgrading, biogas small-scale AD systems might not be financially viable, thus exploring new approaches to improve performance might be required. This study aims to improve the economic feasibility of AD as a mitigation technology by assessing novel approaches through a techno-economic assessment (TEA), including the integration of microbial electrolysis cell (MEC) technology, and the cost of biogas logistics through pipeline optimisation to transport biogas or biomethane. Results indicate that MEC-AD systems, particularly in combined heat and power (CHP) systems, show potential for improved financial viability. Despite critical considerations of operational and capital costs, the MEC-AD system offers advantages by combining production and upgrading processes within the reactor, making small-scale upgrading more affordable. The inclusion of the MEC-AD system on small-scale upgrading increased the revenue generated by 91% with only a 41% rise in overall operational expenditures. In contrast, pipeline optimisation scenarios reveal challenges with small-scale upgrading systems, due to high capital and operational costs, driven by substantial feedstock acquisition expenses. Centralised upgrading offers a promising alternative, significantly reducing required capital expenditure for AD systems compared to on-site upgrading. Further research

is necessary to prioritise connections and optimise biogas flow rates, ultimately enhancing the economic feasibility of biogas pipeline networks.

Keywords: Anaerobic Digestion; Techno-Economic Assessment; Sensitivity analysis; Abatement Cost; Uncertainty analysis.

6.1 Introduction

The Irish government, under its commitments of the Climate Action Plan 2023, is seeking to increase the national production of biomethane and thus decrease dependence on fossil-derived natural gas (1). This will involve the construction of numerous new anaerobic digestion (AD) plants by 2030 which would deliver an annual production of 5.7 TWh of biomethane (1). Strategies will be required to ensure the agriculture sector can deliver on this goal whilst also meeting its sectoral emissions reduction target of 25% (1). The use of feedstocks such as livestock manure (slurry) in AD can help mitigate emissions from livestock production to generate biomethane for its use in the heat and transport sectors (2). Grass silage is often co-digested with slurry to improve the nutrient balance of the digester. However, traditional AD systems can encounter barriers such as low biomethane production due to the low biodegradability of feedstocks – specifically if the grass silage has high lignin and cellulose content (3). Furthermore, if biomethane is the preferred end-product, the relatively high cost of upgrading biogas in small-scale AD systems (as would be evident on Irish farms) can become a significant hurdle, due to elevated capital costs (4). New concepts and strategies will be required going forward to make AD economically viable in such scenarios. The EcoAD project, funded by the Sustainable Energy Authority of Ireland (SEAI), sought to identify more efficient biomethane production scenarios for Ireland (5). The project intended to develop economic solutions for on-farm AD systems using Irish farm-based feedstocks. By assessing the integration of novel technologies to enhance on-farm digestion efficiency, optimising logistics for biogas delivery, and conducting a techno-economic assessment of potential on-farm AD pathways, the project aimed to pave the way for economically sustainable AD implementation.

A key parameter for the optimisation of an AD system is the overall process efficiency and enhancing this parameter can improve the financial performance, as was indicated in Chapter 5. Previous literature studies have explored the enhancement of biogas production while decreasing the specific cost of on-farm AD through novel methods. These include strategies like the addition of trace elements or the identification of optimal co-digestion ratios for grass silage and slurry (6,7). Other novel approaches to improve AD process performance include the use of two-stage AD reactors (8), the use of conductive carbon materials to increase the interspecies electron transfer with graphene (9), and the utilisation of in-situ electro-methanogenesis (10). In particular, the latter holds significance for small-scale AD since enhancing AD performance concentrates biomethane within the reactor, thereby reducing the need for, and the associated expense of, biogas upgrading (10). The microbial-electrolysis cell (MEC) is a concept whereby electrodes are inserted into the AD reactor and facilitate microbe-electrode interactions enhancing digestion and facilitating the conversion of carbon dioxide (CO_2) to methane (CH_4) (11). Currently, this technology is still in development and its techno-economic feasibility has not been assessed.

The integration of MEC into conventional AD systems was evaluated as part of the EcoAD project to improve biomethane production in an Irish context with grass and slurry feedstocks. In the experimental design, the addition of two-electrodes was assessed in enhancing the anaerobic digestion process (12). An assessment was conducted on the electrochemical properties of the electrodes and the variations in voltage to identify the optimal configuration. The use of a modified graphite cathode at an applied voltage of 1.0 V was found to lead to an efficient electron transfer between microbes and electrodes. This enhancement resulted in a 6.5-fold increase in biomethane yield in relation to the electrical energy input. When compared to a traditional AD system, the MEC-AD system demonstrated a notable enhancement in the biomethane yield and methane content in biogas with an increase of 96.8% and 32.5%, respectively. However, this assessment of the MEC-AD concept was conducted at a laboratory scale, thus economic and operational factors need to be considered when translating this research to larger-scale systems. For system scale-up, the reactor configuration, energy conversion efficiency and economic feasibility need to be accounted for (13,14). The commercial development of MEC-AD has previously been undertaken for industrial wastewater treatment, such as through the Ecovolt reactor from Cambrian Innovation (15,16). Nonetheless, the impact of this innovative approach has yet to be evaluated for small-scale on-farm AD plants.

When assessing the feasibility of on-farm AD, a second key consideration is the transportation of the generated biogas or biomethane to the end user. A previous study undertaken by *Ó Céileachair et al.* (17) revealed that more than one-third of Ireland's on-farm biomethane resources are distributed in a decentralised manner, often located at distances exceeding 12.5 km from existing gas grid infrastructure.

This indicates that the biomass resources intended for use as feedstock in on-farm AD systems may be situated beyond the reach of gas grid infrastructure, posing logistical and economic challenges to their utilisation. This dispersion implies a need to optimise the logistics of renewable gas transportation to the end users. The method of delivery to an end-user depends on whether the biogas can be upgraded to biomethane on-site or not. An approach to reduce biogas upgrading costs involves the use of a low-pressure biogas pipeline to a centralised upgrading facility (18,19). However, the specific location of biogas producers will determine the necessity for new grid connections, which will, in turn, influence the scale of investments needed to establish the biogas pipelines (20).

The investment necessary for biogas pipelines will be influenced by the physical layout required between the AD plants and the end users (21). The most cost-effective strategy for pipeline construction involves installation that allows for the shortest feasible path between the producer and the end user (22). However, depending on the number and location of producers, many connections may be required, needing construction through the property of landowners who may not permit such projects. An alternative approach involves using the existing road networks to situate the biogas pipeline, although this approach could lead to disruptions for road users and local business owners during the construction phase (23). A common optimisation technique to minimize pipeline layout length involves the use of a minimum spanning tree (MST). This refers to the most concise route for connecting multiple points (vertices). This can even be further optimised using Steiner nodes which are supplementary vertices within a network that can effectively reduce the total network length while connecting all vertices.

One of the work packages of the EcoAD project examined the optimisation of biogas network logistics in Ireland (24). A methodology employing optimisation software was devised to design layouts for biogas pipelines connecting various AD plants to a biogas user. To assess the optimal arrangement for a network operator, ten AD plants were randomly positioned close to a biogas user, near the national road network, within a designated area of 120 km^2 to identify the best layout for a network operator (24). Through the application of multi-criteria decision analysis (MCDA), the optimal pipeline layout and connection methodology were determined by comparing different pipeline material costs and biogas flowrates. Notably, it was found that the use of Steiner MST could achieve 26% less cost than using a road network MST. This reduction primarily stemmed from the direct correlation between network length and pipeline material costs, along with the biogas flow rate. A longer network would require more materials and a higher flow rate to reach the end user. However, this model exclusively considered pipeline materials as the main investment cost. A more comprehensive analysis would entail accounting for engineering, compression, clean-up, and labour costs (21,25). Additionally, operational and maintenance costs would need to be included as part of the analysis.

It is evident from the literature that there are relatively few techno-economic assessments (TEA) of on-farm AD systems in Ireland (26–28). Furthermore, previous assessments by the author for small scale on-farm AD have proven that these systems can struggle to be financially viable (4), and novel approaches are now required to improve the economic viability of AD as a mitigation technology. One approach may involve the novel AD enhancement measure of MEC-AD to potentially improve the techno-economic performance. Another approach may relate to the optimisation of biogas logistics and the viability of transporting biogas via pipeline to a centralised biogas user, as the financial viability of providing access to energy users from Irish farm-scale AD systems is essential. This study aims to identify the financial requirements through a TEA for the implementation of novel technologies such as MEC for on-farm AD systems in Ireland. Furthermore, the cost of delivering biogas through pipelines to a central upgrading unit will be evaluated as an alternative option to on-site upgrading. The overall objectives of the study concerning the implementation of on-farm AD in Ireland are:

• Compare the techno-economic performance of an on-farm AD system with an integrated microbial electrolysis cell (MEC) as compared to a baseline on-farm AD system.

• Calculate the allowable investment (beyond a baseline AD system) for a MEC-AD system given a specific biogas end-use (boiler, CHP or upgrading)

• Carry out an economic analysis of a biogas pipeline network to a centralised upgrading facility as an alternative to on-site biogas upgrading for on-farm AD systems.

6.2 Methodology

6.2.1 MEC-AD farm-scale scenario

To evaluate the techno-economic performance of MEC-AD, a farm-scale scenario was modelled as a case study. For the economic analysis, the enviro-economic tool developed in Chapter 4 was used to derive economic key indicators, including the net present value (NPV), and overall system revenue. These indicators will be used to assess the novel MEC-AD system in comparison to a baseline (traditional/standard) AD system. Given the absence of specific economic data for farm-scale AD systems integrating MEC as a technology to enhance biogas production performance, the results obtained from a lab-scale two-electrode system previously assessed by *Ning et al.* (12) were used.

The system was modelled on a single-stage continuously stirred-tank reactor (CSTR) incorporating the addition of a modified graphite plate as the cathode and a graphite rod as the anode. The process conditions were set at a temperature of 37 °C (mesophilic range) utilising a combination of biomass feedstock from on-farm sources, including grass silage and cattle slurry at a volatile solid (VS) ratio of 4:1 (29). The cattle slurry ($C_{2.77}H_{4.02}O_{3.84}N_{0.09}$) was sourced from a local dairy farm located in Co. Cork, Ireland, whilst the grass silage came from an early-cut perennial ryegrass (*Lolium perenne*) ($C_{3.34}H_{5.02}O_{3.29}N_{0.16}$). Detailed properties of both feedstocks can be found in Table 6-1.

Table 6-25 Feedstock properties used in the MEC-AD assessment. Adapted grom Ning et al. (12).

Parameter	Cattle Slurry	Grass Silage
Dry Matter (DM[a]) [%]	8.3	22.6
Volatile solids (VS[b]) [%]	6.5	20.7
VS / DM [%]	78.31	91.6
CH_4 in biogas (v/v[c]) [%]	45.69	48.09

[a] DM: Dry matter.
[b] VS: Volatile solids.
[C] V/V: Volume concentration for volume of CH_4 per volume of biogas.

To calculate the total amount of feedstock required, a farm-scale scenario was modelled containing 90 dairy cows based on the average herd size for dairy farms in Ireland for 2021 (30). Slurry production per head of cattle was calculated based on a 0.33 m^3, or 0.33 tonnes wet weight (t_{wwt}) per week (31). Annual production was then calculated on the number of weeks the livestock were housed indoors. This period varies according to the farm location in Ireland, typically ranging from 16 to 22 weeks, following Good Agricultural Practice (GAP) guidelines for the Protection of

Waters (32). A period of 18 weeks indoors was assumed for the scenario, for a total annual production of 535 t_{wwt} a^{-1} of dairy slurry. Considering the volatile solids (VS) content of dairy slurry (as detailed in Table 6-1), this equates to 35 tVS a^{-1}.

To obtain the same energy conversion efficiency as the laboratory-scale experiment, the required amount of grass silage feedstock to co-digest with cattle slurry at a VS ratio of 4:1 was calculated. This equated to 139 tVS a^{-1} of grass silage for co-digestion with slurry. Based on the VS content of grass silage (Table 6-1) a total of 672 t_{wwt} a^{-1} would be required. Assuming a grass silage yield of 10 tonnes of dry matter (tDM) per hectare (33), and accounting for the dry matter (DM) content of grass (as detailed in Table 6-1), an area of 15 ha of would be required towards grass silage production to be used as AD feedstock.

The biogas production (V_{AD}) from the co-digestion was calculated in cubic metres per annum (m^3 a^{-1}) based on the VS content of the feedstock mixture as per Equation 6.1. A methane leakage of 2% of the overall volumetric production was considered based on prior literature on existing biogas systems (34,35).

Equation 6-1 Biogas production based on the methane yield of co-digestion of cattle slurry and grass silage.

$$V_{AD}\left(\frac{m^3}{a}\right) = \frac{(VS_{FM}) * SMY_{FM}}{\frac{\%CH_{4_{FM}}}{100}}$$

In Equation 6-1, VS_{FM} is the VS content of the feedstock mix in kgVS a^{-1} (as per Table 6-1), SMY_{FM} is the specific methane yield of the feedstock mix in m^3 $kgVS^{-1}$, and $\%CH_{4_{FM}}$ is the methane content in biogas which were 193 m^3 $kgVS^{-1}$ and 52.2% respectively based on the results of the laboratory experiments (12). With the MEC-AD system, a notable increase in biogas production of 96.8% was considered for SMY_{FM}. Additionally, an increase in the concentration of CH_4 in the biogas was considered increasing to 69.2%. This increase can be attributed to the electrochemical conversion of CO_2 to CH_4 in-situ, facilitated by the presence of the electrodes (11).

The baseline AD system and the MEC-AD system were assessed using three different biogas end-use configurations (Boiler, Combined Heat and Power (CHP), and biogas upgrading (UPG)), previously evaluated by the author (as per Chapter 4 and 5), these include:

- Boiler Configuration: In this setup, the heat generated by a biogas boiler was utilised in the immediate vicinity by large energy heat users. The overall gross energy output was calculated assuming a boiler efficiency of 90%, based on values assessed for natural gas boilers (36,37). Part of the heat produced covered the thermal demand of the AD process, while electricity from the grid fulfilled the system's electricity requirements.
- CHP Configuration: In this configuration heat and electricity were produced through the use of a small CHP unit (less than 70 kW_{el}) with a 35% electrical efficiency and a 50% thermal efficiency (27,28,38,39). The thermal and electric demand of the AD process was assumed to be covered by part of the energy produced by the CHP unit.
- UPG Configuration: For this configuration, biomethane was produced via biogas upgrading using water scrubbing technology, selected based on prior literature which recommended this approach for small-scale systems (40). A 94% methane recovery rate of the gross biogas production was considered (6% of the methane not captured was recirculated at the bottom of the scrubber) with an electrical demand of 0.45 kWh m^{-3} of biogas (40–42). It was assumed that electricity from the grid covered the electrical demands of both AD and upgrading, while a natural gas boiler, fuelled by natural gas from the grid, met the thermal demand of the AD process.

The electric demand of the baseline AD system was assumed to be 10 kWh per t_{wwt} of feedstock per annum based on prior literature values (43–46). While the electrical demand of the MEC-AD system accounted for an additional electrical demand which was 180 kWh tVS^{-1} considering an optimal voltage of 1.0 V based on the results from the laboratory-scale experiments (12). The results were then compared between the MEC-AD system and the baseline AD system to assess the overall improvements of the integration of the novel technology.

6.2.2 Biogas pipeline optimisation scenario

A case study by *Ó Céileachair et al.* (24) that previously evaluated an area of 120 km^2 in Ireland, was used for the economic analysis of the biogas pipeline network. The enviro-economic tool developed in Chapter 4 was also used to derive key indicators (NPV and revenues) to assess the viability of transporting biogas via pipeline to a centralised biogas user. The location of 10 AD plants in the vicinity of a biogas user (in this case an upgrading facility or a centralised injection point) (Figure 6-1) were selected randomly with different biogas production rates based on the typical biogas production output of a small on-farm AD plant (24). Each plant considered to have a baseline AD system producing biogas with the same number of dairy cows (90 in total) having a similar input of cattle slurry while the area required towards grass silage production to be used as AD feedstock will be different based on the farm area available as shown in Table 6-2.

Table 6-2 AD plants feedstock input, farmland area, and biogas outputs. Adapted from Ó Céileachair et al.(24).

AD plant	Feedstock Input			Biogas Output	
	Cattle Slurry (t_{wwt})	Grass Silage (t_{wwt})	Farm Area (ha)	(m^3 hr^{-1})	(m^3 $week^{-1}$)
1	534	1989	45	29.8	5,000
2	534	1815	41	27.4	4,600
3	534	1642	37	25.0	4,200
4	534	1468	33	22.6	3,800
5	534	1294	29	20.2	3,400
6	534	1128	25.48	17.9	3,000
7	534	954	21.55	15.5	2,600
8	534	781	17.63	13.1	2,200
9	534	607	13.7	10.7	1,800
10	534	433	9.78	8.3	1,400
Total				**190.5**	**32,000**

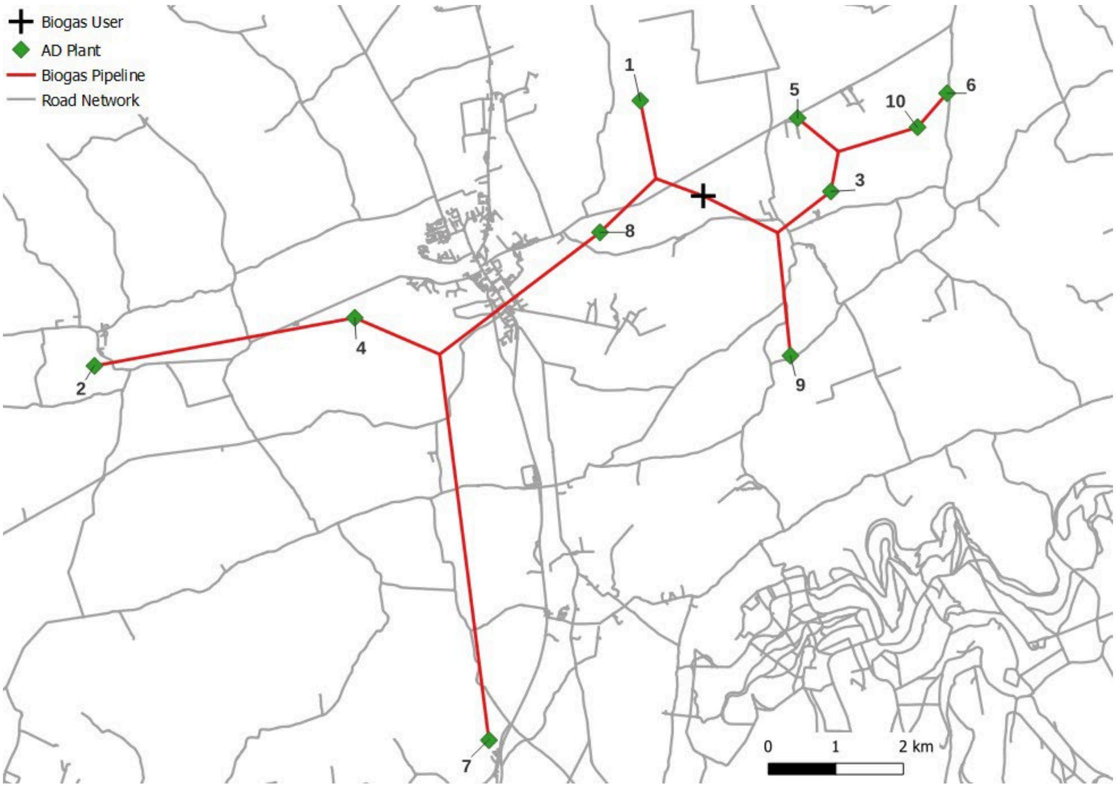

Figure 6-1 Location of 10 AD plants around a biogas user through a direct pipeline network. An area of 120 km² in Ireland was used to assess the optimisation of a biogas pipeline. Adapted from Ó Céileachair et al. (24).

The pipeline layout (Figure 6-1) was derived from the findings of Ó Céileachair et al. (24), specifically from the Steiner MST results, particularly the MST.X scenario. This scenario outlines the shortest possible route for connecting all 10 AD plants to the biogas user via the biogas pipeline. This layout was drawn in QGIS, an open-source geographic information system. The scenario was a result of a lexicographic heuristic model, in which the pipeline network was designed by connecting nodes in order of biogas output to maximize biogas flow rate. Then the necessary length of pipelines connecting the 10 AD plants to the biogas user (central upgrading facility or central injection point) were calculated. Based on the result of the analysis the pipeline material cost was based on the use of SNAP, a software provided by DNV (an internationally accredited registrar and classification society) designed for low-pressure pipeline network analysis (24). Using the pipe length (m) and the total amount of nodes required to connect all the AD plants to the end user SNAP calculated the minimal pipe diameter required based on the overall pressure from the biogas producers to the biogas end user. This included for smaller pipelines, gradually increasing in size based on the desired gauge pressure which resulted in 3 nominal diameters to minimise the network cost as shown in Table 6-3. (24,47).

Table 6-3 Required pipeline diameters, pipeline lengths and pipeline material cost required for the 10 AD plants. Prices were based on polyethylene pipes (SDR17 PN10) sourced from a local supplier (Irish Tube & Fittings Supply Limited). Adapted from Ó Céileachair et al. (24).

Nominal Diameter (mm)	Unit Cost (€ m^{-1})	Required Length (km)	Cost (€)
63	5.09	4.45	173,062.25
90	6.18	15.09	
125	11.72	4.87	
Total Length (km)		24.42	

The AD plants were numbered from 1 to 10 based on their total biogas production, arranged from the largest to the smallest producer. To calculate the most cost-effective method for an overall biogas network two different scenarios were considered. For the first scenario each on-farm AD plant had its own upgrading facility (AD-UF) (based on the UPG configuration). The produced biomethane was assumed to be fed to a centralised injection point through pipelines to maximise transportation efficiency to the gas grid (Figure 6-2). Water scrubbing was selected as the upgrading technology for each on-farm AD plant, given its prior use in small-scale systems with low biogas flow rates (40)..The overall energy output of biomethane and electric demand were calculated based on the parameters used in the upgrading configuration as shown on section 6.2.1. For this scenario, the biomethane was assumed to be transported using the pipeline networks as per figure 6-1 without the need of compression. As water scrubbing operates as a pressurized upgrading system, the feeding to a pipeline network operating under 5 bar can be done directly (40).

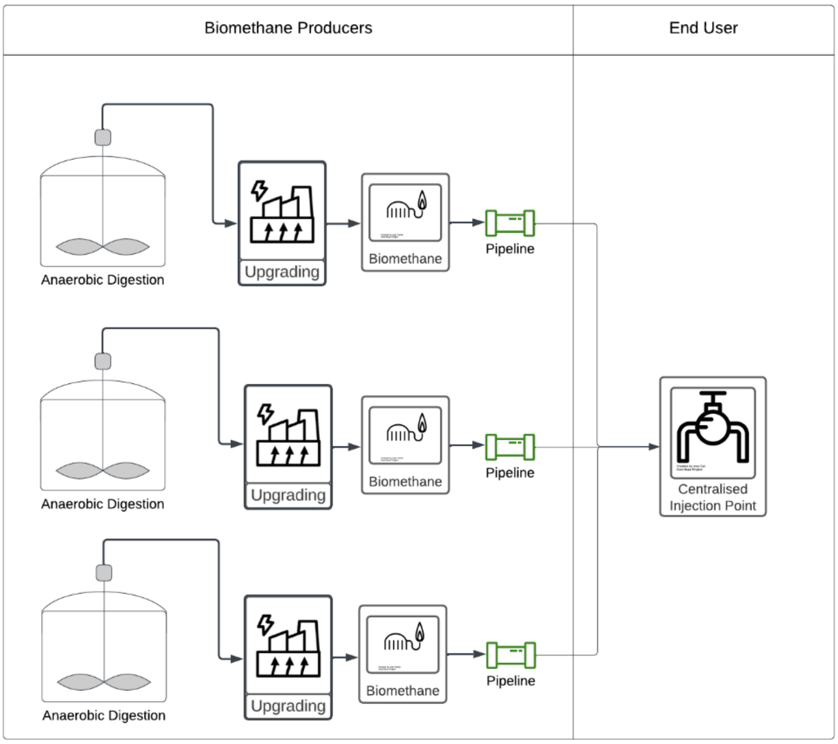

Figure 6-2 Centralised injection point diagram.

The second scenario had each AD plant feed the biogas to a centralised upgrading plant (AD-CUP) with a demand equivalent to the total biogas produced by the 10 AD plants. The produced biomethane is then delivered to the consumers via the gas grid. For the calculations at the AD plants the biogas conditions were based on standard temperature and pressure (STP) values at 0°C with an absolute pressure of 1.013 bar. While for the design of the pipeline network as per the code of operations of the Irish gas network operator's (48) the biogas conditions were based on a temperature of 15 °C with a pressure of 1.163 bar were assumed for the biogas user. The network assumed that each farm supplied biogas to a centralised upgrading unit through smaller pipelines, gradually increasing in size based on the desired gauge pressure at the biogas user (1.163 bar) as illustrated in Figure 6-3. It was assumed that the digester site had basic biogas cleaning and a compressor. The biogas was assumed to be processed under atmospheric pressure; a reciprocating compressor suitable for small-pressure raw biogas pipeline systems was employed. The compressor's total power was 13.57 kW, calculated using an online reciprocating compressor calculator (49). Detailed calculations can be found in Appendix D1.

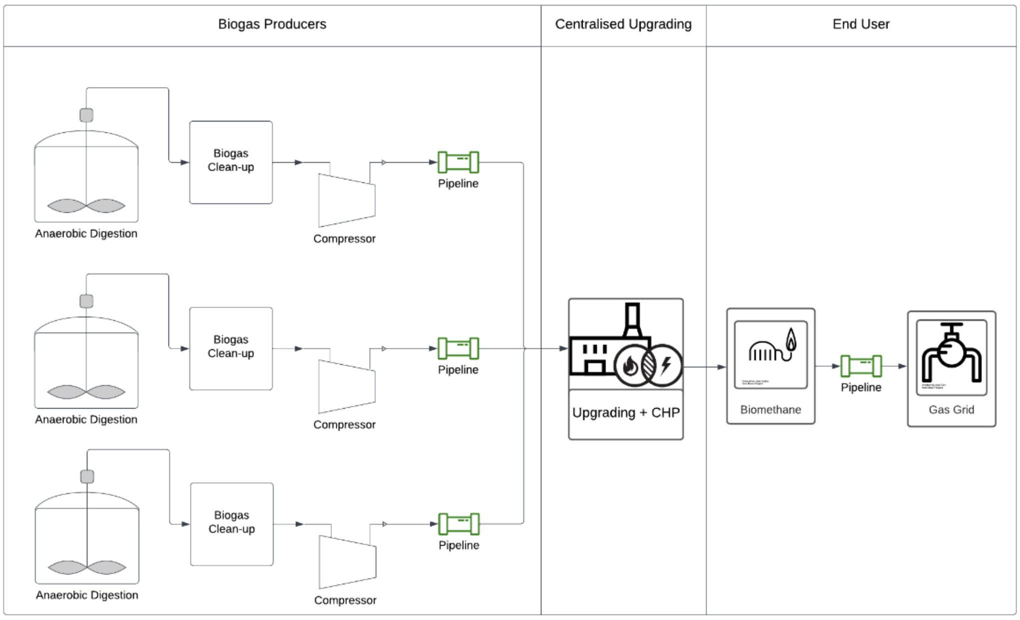

Figure 6-3 Centralised biomethane production diagram.

6.2.3 Economic assumptions

To undertake the techno-economic analysis, an enviro-economic tool previously developed for on-farm AD was used (4). To evaluate the profitability of the MEC-AD scenario and the pipeline optimisation scenario the economic outputs were calculated considering a 15-year system lifetime, commonly used for on-farm AD systems (27,28).

Equation 6.2 Net Present Value calculation.

$$NPV(€) = -C_F + \sum_{t=0}^{L} \frac{(C_I)}{(1+r)^t}$$

The NPV for each scenario was calculated as per Equation 6.2, where C_F represent the capital cost (CAPEX) of the scenario, C_I represent the net cash flow for period t, L represent the lifetime of the system in years, and r is the discount rate, which was considered at 10 %, reflecting an average value in literature for biogas facilities (50).

In each scenario calculation, an initial capital cost (C_F) was used, considering half of the CAPEX as an initial payment by the developer. Additionally, the net cash flow per year (C_I) accounted for a loan repayment for the other half of the CAPEX (10 years), insurance, maintenance, and administrative costs (as detailed in Chapter 4), while the operational cost (OPEX) and revenues were calculated based on the configuration of the system.

The calculation of the OPEX of each scenario included for the labour costs for the operation of the AD and upgrading systems, the annual fuel and electricity requirements of each system configuration (as per Section 6.2.1) and the feedstock acquisition cost. Detailed values for the OPEX can be found in Table 6-4.

Table 6-4 Operational cost values used scenarios based on the configuration selected.

Variable	Value	Source
Labour cost of AD process [€ hr^{-1}]	15	(28)
Labour cost of Upgrading [€ hr^{-1}]	15	(28)
Fuel cost (Natural gas) [€ MWh^{-1}]	134.5	(51)
Electricity Cost [€ MWh^{-1}]	349	(51)
Feedstock Cost (Silage) [€ t_{wwt}^{-1}]	43	(52)

For all scenarios, a revenue stream based on the use of digestate as biofertiliser to displace synthetic fertiliser was considered based on a set value of 2.7 € kgN^{-1}. Depending on the system configuration, various revenue streams were considered, reflecting the overall energy production.

For the baseline AD system and the MEC-AD systems, based on the boiler and CHP configuration, the heat generated considered two revenue streams: one from the support scheme for renewable heat (SSHR) valued at 29.5 € MWh^{-1} (53), and the other from the sale of heat based on customer prices for district heating with a value of 60 € MWh^{-1} (54). Revenue for electricity generation considered only the renewable electricity support scheme (RESS) with a value of 74.08 € MWh^{-1} (53). For the biomethane configuration the sale of biomethane was set at a selling price of 83.7 € MWh-1, reflecting the average value for natural gas for businesses for the first half of 2023 (57).

For the pipeline optimisation two sources of revenue were considered based on the scenario. For the AD-UF scenario a revenue base from the sale of biogas from the baseline AD system was priced at 0.2€ m^{-3} based on the bioenergy market value

(55,56). Meanwhile, the AD-CUP scenario considered each system to have an upgrading unit so the sale of biomethane was considered at 83.7 € MWh^{-1} (57).

For the MEC-AD scenarios, the CAPEX for baseline AD system was based on previous assessed systems in Ireland (4). This accounted for three different biogas end-use configurations (Section 6.2.1). As there is no previous financial information on MEC-AD systems in the literature, the CAPEX allocated for the scenario was calculated based on the additional revenue generated by the increased production of biogas and biomethane achieved by integrating the novel technology. To carry out this calculation, the Goal Seek function of Microsoft Excel was used to determine the maximum amount of investment that could be allocated for the MEC-AD CAPEX to match the NPV of the baseline AD system. This calculation accounts for the additional operational cost resulting from the electrical demand of the MEC system.

For the pipeline optimisation scenarios, the AD-UF scenario considered the CAPEX of each individual farm based on the upgrading configuration as per section 6.2.1. For this scenario, it was assumed that the installation and material cost of the pipeline (Figure 6-1) was assumed by the network operator. As such each farm would pay an additional operational cost in the form of a transmission tariff (C_T) for the use of the transmission system as per Equation 6.3.

Equation 6.3 Calculation of the overall transmission tariff for the pipeline optimisation scenarios.

$$C_T\ (€) = \left[E_{TC_1} * \frac{V_{ADa} * cv_{CH_4}}{3.6} + E_{TC_2} * \frac{V_{ADd} * cv_{CH_4}}{3.6}\right] + \left[E_{XC_1} * \frac{V_{ADa} * cv_{CH_4}}{3.6} + E_{XC_2} * \frac{V_{ADd} * cv_{CH_4}}{3.6}\right]$$

The tariff for each farm (C_T) was calculated taking in account entry and exit tariffs charged by the network operator (58). Entry tariffs comprise the renewable natural gas annual commodity tariff (E_{TC}) set at 0.15 € MWh^{-1}, and the capacity tariff (E_{TC_2}) valued at 190.93€ MWh^{-1}. Exit tariffs consist of the gas commodity tariff (E_{XC_1}) at 0.31 € MWh^{-1}, and the capacity tariff (E_{XC_2}) at 612.59 € MWh^{-1}. Gas commodity tariffs were calculated based on the annual biomethane output of each farm (V_{ADa}), while the capacity tariffs considered the peak daily capacity of biomethane production (V_{ADd}). Both were calculated based on the production of each farm as per Table 6-2. This assuming an overall calorific value of biomethane of 35.7 MJ Nm^{-}

$^{3}CH_4$ (cv_{CH_4}), at STP with a methane density of 0.714 kg m^{-3} and a lower heating value for methane of 50 MJ kg^{-1}.

As data on the installation cost of gas pipelines in Ireland is limited in the literature, for the AD-CUP scenarios the allowed pipeline installation cost was calculated using the Goal Seek function of Microsoft Excel compared to the NPV of the AD-UF scenario. For this the initial CAPEX, each on-farm AD systems were set at 27 € $t_{feedstock}^{-1}$ a^{-1} based on previous evaluated systems in Ireland (59,60). To this cost, the pipeline material cost (referenced in Table 6-3) was assumed to be divide equally between the 10 farms. Then using the Goal Seek function, the maximum amount of investment that could be assigned for the CAPEX of each farm for to the installation of the pipeline was calculated by matching it to the NPV of each of the farms in the AD-UF scenarios.

6.3 Results and Discussion

6.3.1 Baseline AD vs. MEC-AD systems

One of the primary distinctions between MEC-AD reactors to baseline AD systems is the enhancement of biogas and biomethane yields - achieved by the integration of electrodes into the reactor. This subsequently results in increased revenues due to additional biogas/biomethane sales. However, it also leads to an increase in operational costs due to the electrical demand of the MEC-AD system.

Based on the different systems evaluated, the configuration that performed the best financially was the MEC-AD system with the UPG configuration. This system achieved an increase in revenues of 91%, as seen in Figure 6-4, accompanied by a modest 41% rise in overall operational expenditures (OPEX), as depicted in Figure 6-5. The CHP configuration demonstrated the highest revenue increase, by 111%, albeit with a corresponding 63% increase in OPEX. On the other hand, the Boiler configuration showed a balanced increase in both revenue and OPEX, both standing at 105%. Notably, this configuration nearly matched the overall revenue achieved by the UPG configuration, making it quite a competitive option.

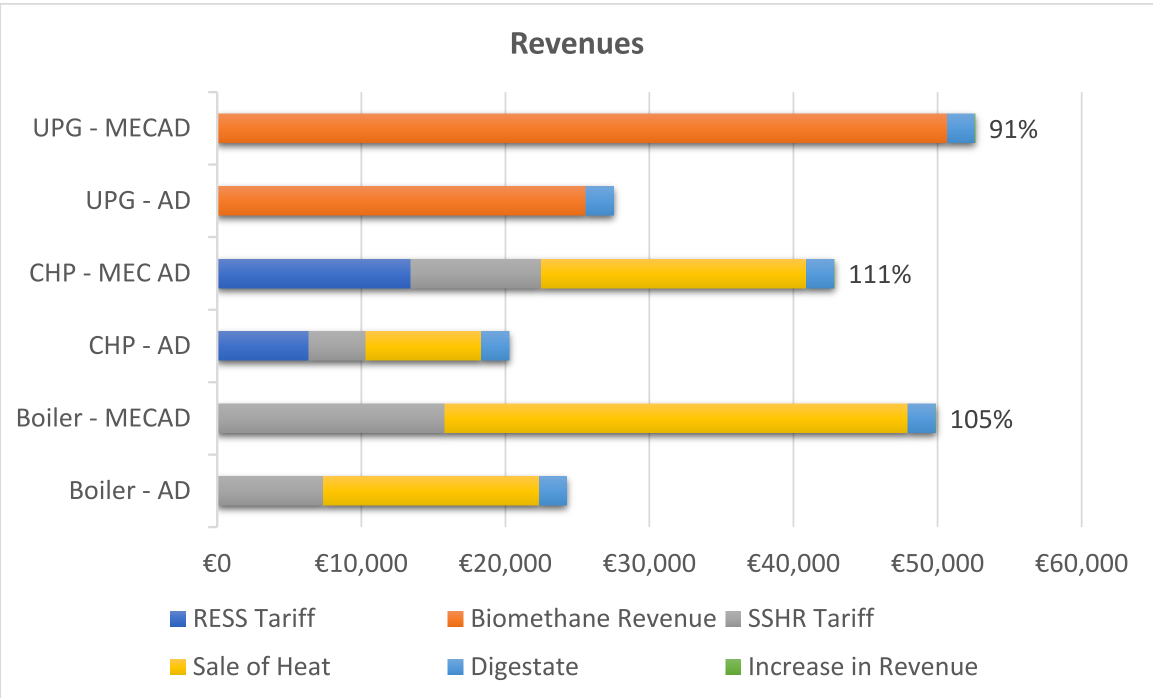

Figure 6-4 Revenues of baseline AD systems and MEC-AD systems considering 3 different end-use configurations (Boiler-production of heat, CHP - production of heat and energy, and UPG - production of biomethane)

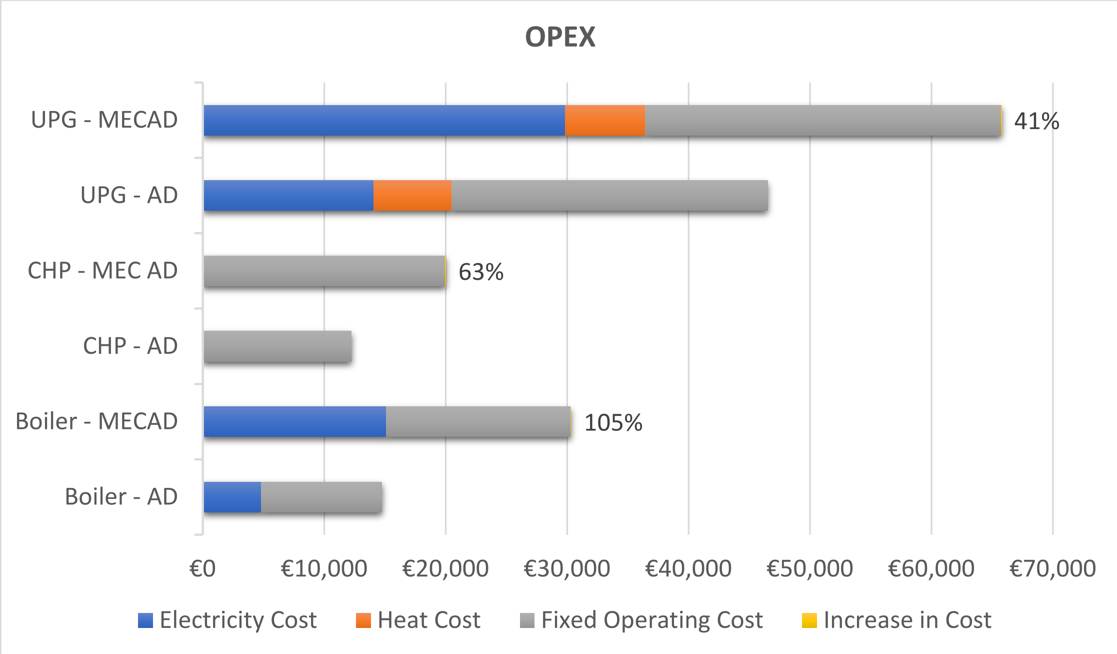

Figure 6-5 Operational cost of baseline AD systems and MEC-AD systems considering 3 different end-use configurations (Boiler-production of heat, CHP - production of heat and energy, and UPG - production of biomethane)

The overall results from the economic analysis of the baseline AD systems proved to be not financially viable having negative NPV from the economic analysis (as per Table 6-5). As previously demonstrated by the author (Chapter 4 and 5), small-scale farm-based AD systems can suffer from increased operating costs due to the high price of grass silage (4). Furthermore, considering recent rises in energy prices, the financial viability of such projects could further diminish. This is evident in the 47% increase in electricity prices observed between the last quarter of 2022 and the first quarter of 2023, rising from €299 per MWh to €400.6 per MWh for a consumption band between 20 to 500 MWh (51).

One of the main advantages of integrating MEC-AD technology is its ability to combine the biogas production and upgrading processes within the reactor, thereby reducing the volume of biogas required to be upgraded (11). In the case of the upgrading configuration, this translates to a lower energy requirement for the upgrading process compared to the baseline system, due to a 69.2% increase in the concentration of CH_4 in the biogas coming from the digester (12).

The results shown in Table 6-5 indicate a 98% increase in biomethane production with only a 49% increase in electric demand for upgrading for the MEC-AD upgrading configuration as compared to the baseline system. Accounting for the additional 31,146 m^3 of biomethane production, the electrical energy input required for the MEC-AD only consumes 9.87% of the total energy produced. This demonstrates that integrating this technology can be highly beneficial for small-scale upgrading systems, increasing biomethane production while still maintaining an overall cost-effective production.

Comparing the overall results of the NPV between baseline systems and MEC-AD systems, the configuration that would allow the maximum amount of investment allocated for the CAPEX of the MEC system would be the CHP configuration. One of the main advantages of this configuration is the reduction of operational costs due to energy inputs, achieved by using part of the biogas produced as a source of renewable energy to cover the electric and thermal demand of the system. Although the UPG configuration would derive the greatest benefit from the integration of the MEC system, the high operational and capital costs of the small-scale upgrading system reduced the amount of CAPEX that could be allocated to this novel technology.

While the CHP configuration appears to offer the most favourable financial prospects for integrating MEC-AD technology, operational and capital cost considerations remain significant factors affecting the feasibility of adopting this innovative approach in small-scale upgrading systems. Further analysis would be required to assess how the cost of the carbon anodes and cathodes would translate into large-scale applications. *Escapa et al.* (15) found that, for large-scale applications, anode and cathode fabrications comprising of graphene sponge could prove to be an easy and relatively low-cost solution, with an associated cost of $4 USD per m^2. Although graphene differs from the graphite as a carbon-based material, the overall cost-effectiveness could be assessed in future studies to compare its effect on the production of biomethane and its energy efficiency against graphite.

Table 6-5 Results from the baseline AD and the MEC-AD scenarios.

Configuration / Variable	Upgrading		CHP		Boiler	
	Baseline	**MEC-AD**	**Baseline**	**MEC-AD**	**Baseline**	**MEC-AD**
Biogas Production (m^3)	62,828	93,839	62,828	93,839	62,828	93,839
Biomethane Production (m^3)	31,782	62,928	-	-	-	-
Electric Demand of AD (kWh a^{-1})	12,061	12,061	-	-	12,061	12,061
Electric Demand of Upgrading (kWh a^{-1})	28,273	42,228	-	-	-	-
Electric Demand of MEC-AD (kWh a^{-1})	-	31,276	-	31,276	-	31,276
Total Electrical Demand (kWh a^{-1})	40,334	85,565	-	-	12,061	43,338
NPV (€)	- 563,886	- 563,886	- 292,703	- 292,703	- 243,250	- 243,250
CAPEX (€)	191,377	251,806	128,863	269,411	86,842	182,093
Allowable Investment for MEC-AD (€)		60,429		140,548		95,251

6.3.2 Biogas pipeline optimisation economic results

As previously assessed by the author, the cost of biogas upgrading is highly dependent on the scale of the AD plant due to economies of scale (4). Table 6-6 displays the results of the economic analysis for the 10 AD plants in the AD-UF scenario. Overall, the results indicate that small-scale upgrading was not financially viable having negative NPV due to the high capital and operational costs. The main factor driving the high operational costs was the feedstock acquisition cost, representing between 39% to 59% of the overall OPEX. In contrast, the overall transmission cost represented only between 2% to 3% of the overall OPEX of each farm. Detailed results of the OPEX for the scenario can be found in Appendix D2.

Table 6-6 Economic results of the AD-UF scenarios for the 10 AD plants.

AD plant	CAPEX (€)	OPEX (€)	Revenues (€)	NPV (€)	Biomethane Produced (m^3 a^{-1})
1	569,311	222,016	107,475	-1,444,421	121,966
2	528,147	227,505	98,765	-1,340,085	112,136
3	486,983	208,965	90,055	-1,235,879	102,320
4	445,819	190,415	81,346	-1,131,673	92,498
5	404,654	171,853	72,636	-1,027,289	82,675
6	365,205	154,052	64,290	-927,528	73,261
7	324,041	135,461	55,580	-823,144	63,439
8	282,877	116,850	46,870	-718,938	53,616
9	241,713	98,215	38,161	-614,732	43,793
10	200,549	79,547	29,451	-510,347	33,970
Totals	**3,849,299**	**1,604,877**	**684,630**	**-9,774,036**	**779,675**

One advantage of the AD-CUP scenario over the AD-UF scenario is the overall reduction in the required CAPEX investment for the AD system. The total CAPEX investment for the 10 AD farms, considering only the installation of basic AD systems, represents only 21.5% of the overall investment required for on-site upgrading systems. Comparing the overall results of the NPV between the AD-UF and AD-CUP scenarios, as shown in Table 6-7, indicates an overall maximum investment for the network cost of €372,790. This allows for an investment of more than double the cost of the pipeline materials, which could be allocated to cover construction, ongoing maintenance, and land access costs.

One factor that directly impacted the financial viability of some farms in the AD-CUP scenario was the compression requirements. Generally, power requirements for compressing raw biogas can be higher than those required for upgrading, primarily because there is no need to compress the additional CO_2 found in the mix of raw biogas compared to biomethane (61). For the AD plants, the compression energy requirement represented an overall consumption between 0.49 to 1.62 kWh per Nm^3 of raw biogas. As shown in the results of Table 6-7, for the AD plants numbered 7 to 10, the overall energy requirements for compressing the raw biogas translated into higher OPEX, which could not be covered by the revenues generated, making them less financially viable than other farms in the AD-CUP scenario.

Based on these results, additional analysis is required to determine the connection order for AD plants with lower flow rates. As previously noted by *Ó Céileachair et* *al.* (24), the connection order of AD plants could be determined based on the priorities of the biogas user, in this case, the central upgrading facility. The aim would be to improve the biogas flow rate between farms with low production to ensure sufficient gas flow, thereby reducing the power consumption of compression. Once the connection points with adequate biogas flow rates are identified, the compression step can be relocated to those points to reduce the overall power consumption of compression.

Table 6-7 Economic results for the AD-CUP scenarios for the 10 AD plants

AD plant	CAPEX (€)	OPEX (€)	Revenues (€)	NPV (€)	Allowed Network Cost (€)
1	114,362	193,214	57,509	-1,293,205	117,735
2	107,345	180,732	52,811	-1,217,444	95,487
3	100,327	168,292	48,128	-1,141,910	73,163
4	93,309	155,851	43,446	-1,066,376	50,839
5	86,292	143,390	38,756	-990,728	28,465
6	79,566	131,480	34,274	-918,408	7,101
7	72,549	119,019	29,584	-842,761	0
8	65,531	106,579	24,902	-767,227	0
9	58,513	94,138	20,220	-691,693	0
10	51,496	81,677	15,529	-616,045	0
Totals	**829,289**	**1,374,373**	**365,158**	**-9,545,796**	**372,790**

6.4 Conclusion

Based on the overall results it was found the integration of the microbial electrolysis cell system might be a cost-effective solution to increase the financial viability of baseline on-farm AD systems. The economic analysis revealed that while the MEC-AD system, particularly in configurations such as CHP, shows potential for improved financial viability, operational and capital costs remain critical considerations for its viability.

The ability of the MEC-AD system to combine production and upgrading processes within the reactor offers a unique advantage to make small-scale upgrading more affordable. Specifically, the integration of the system increased revenues by 91% accompanied by only a 41% rise in overall operational expenditures. Additionally, comparing the baseline system to the MEC-AD upgrading configuration, a 98% increase in biomethane production with only a 49% increase in electric demand for upgrading, of which 9.87% of the total energy produced was the electric energy input required for the MEC-AD system.

In the case of the pipeline optimisation scenarios, the results indicates that small-scale upgrading systems may not be financially viable due to high capital and operational costs, particularly driven by substantial feedstock acquisition expenses. In contrast, the centralised upgrading approach offers a more promising alternative, with a significant reduction in the required CAPEX investment for AD systems compared to on-site upgrading systems.

The analysis provides insights into the overall allowable network cost for farmers to install biogas pipelines compared to the cost of contracting with a network provider. But to achieve an optimal optimisation at an affordable price, additional research to strategically prioritising connections and optimising biogas flow rates between farms is required. This to allow the reduction of power consumption for compression, further enhancing the economic feasibility of biogas pipeline networks.

References

1. Government of Ireland. Climate Action Plan 2023 [Internet]. 2023 [cited 2023 May 2]. Available from: https://www.gov.ie/en/publication/7bd8c-climate-action-plan-2023/

2. Beausang C, McDonnell K, Murphy F. Assessing the environmental sustainability of grass silage and cattle slurry for biogas production. J Clean Prod. 2021 May 20;298:126838.

3. Monlau F, Sambusiti C, Barakat A, Guo XM, Latrille E, Trably E, et al. Predictive models of biohydrogen and biomethane production based on the compositional and structural features of lignocellulosic materials. Environ Sci Technol [Internet]. 2012 Nov 6 [cited 2023 Aug 14];46(21):12217–25. Available from: https://pubs-acs-org.ucc.idm.oclc.org/doi/full/10.1021/es303132t

4. Diaz Huerta J, Bose A, Wall DM, Murphy JD, O'Shea R. Assessing the cost variability of emissions abatement in small-scale on-farm anaerobic digestion. DeCarbon [Internet]. 2023 Jun 1 [cited 2023 Jun 9];1:100008. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2949881323000082

5. MaREI. Developing Economic solutions for on-farm Anaerobic Digestion technologies under Irish conditions (EcoAD). [Internet]. 2023 [cited 2023 Sep 4]. Available from: https://www.marei.ie/project/ecoad/

6. Wall DM, Straccialini B, Allen E, Nolan P, Herrmann C, O'Kiely P, et al. Investigation of effect of particle size and rumen fluid addition on specific methane yields of high lignocellulose grass silage. Bioresour Technol. 2015 Sep;192:266–71.

7. Wall DM, O'Kiely P, Murphy JD. The potential for biomethane from grass and slurry to satisfy renewable energy targets. Bioresour Technol [Internet]. 2013;149:425–31. Available from: https://www.sciencedirect.com/science/article/pii/S0960852413015265

8. Voelklein MA, Jacob A, O' Shea R, Murphy JD. Assessment of increasing loading rate on two-stage digestion of food waste. Bioresour Technol. 2016 Feb;202:172–80.

9. Lin R, Cheng J, Zhang J, Zhou J, Cen K, Murphy JD. Boosting biomethane yield and production rate with graphene: The potential of direct interspecies electron transfer in anaerobic digestion. Bioresour Technol. 2017 Sep;239:345–52.

10. Blasco-Gómez R, Batlle-Vilanova P, Villano M, Balaguer M, Colprim J, Puig S. On the Edge of Research and Technological Application: A Critical Review of Electromethanogenesis. Int J Mol Sci. 2017 Apr 20;18(4):874.

11. Ning X, Lin R, O'Shea R, Wall D, Deng C, Wu B, et al. Emerging bioelectrochemical technologies for biogas production and upgrading in cascading circular bioenergy systems. iScience. 2021 Sep 24;24(9):102998.

12. Ning X, Lin R, Mao J, Deng C, Ding L, O'Shea R, et al. Improving the efficiency of anaerobic digestion and optimising in-situ CO2 bioconversion through the enhanced local electric field at the microbe-electrode interface. Energy Convers Manag. 2024 Mar;304:118245.

13. Jourdin L, Burdyny T. Microbial Electrosynthesis: Where Do We Go from Here? Trends Biotechnol. 2021 Apr;39(4):359–69.

14. Prévoteau A, Carvajal-Arroyo JM, Ganigué R, Rabaey K. Microbial electrosynthesis from CO2: forever a promise? Curr Opin Biotechnol. 2020 Apr;62:48–57.

15. Escapa A, Mateos R, Martínez EJ, Blanes J. Microbial electrolysis cells: An emerging technology for wastewater treatment and energy recovery. From laboratory to pilot plant and beyond. Renewable and Sustainable Energy Reviews. 2016 Mar;55:942–56.

16. Katuri KP, Ali M, Saikaly PE. The role of microbial electrolysis cell in urban wastewater treatment: integration options, challenges, and prospects. Curr Opin Biotechnol. 2019 Jun;57:101–10.

17. Ó Céileachair D, O'Shea R, Murphy JD, Wall DM. Alternative energy management strategies for large industry in non-gas-grid regions using on-farm biomethane. Appl Energy. 2021 Dec 1;303:117627.

18. IEA Bioenergy Task 37. Green Gas Hub. Provision of biogas by farmers by pipe to a Green Gas Hub with a centralised upgrading process. 2017.

19. Aemetis Inc. Renewable Natural Gas [Internet]. 2022 [cited 2023 Aug 15]. Available from: https://www.aemetis.com/products/renewable-natural-gas/

20. IEA. The outlook for biogas and biomethane to 2040 – Outlook for biogas and biomethane: Prospects for organic growth [Internet]. 2020 [cited 2023 Aug 15]. Available from: https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/the-outlook-for-biogas-and-biomethane-to-2040

21. Havrysh V, Nitsenko V, Bilan Y, Streimikiene D. Assessment of optimal location for a centralized biogas upgrading facility. Energy & Environment. 2019 May 24;30(3):462–80.

22. Ó Céileachair D, O'Callaghan S, Wall DM, Goulding D, O'Connor D, Murphy JD, et al. Logistical considerations and challenges in deploying virtual biomethane pipelines to serve on-farm biogas plants. J Clean Prod. 2023 Jun;407:137075.

23. Gas Network Ireland. Project Information. 2018 [cited 2023 Aug 28]. Natural gas is coming to Center Parcs, Co. Longford. Available from: https://www.gasnetworks.ie/corporate/company/our-network/projects/current-and-planned/new-towns/Gas-to-Center-Parcs-Brochure.pdf

24. Céileachair DÓ, O'Shea R, Murphy JD, Wall DM. A methodology for designing biogas pipelines. Fuel. 2024 Apr;361:130633.

25. Peppers J, Li Y, Xue J, Chen X, Alaimo C, Wong L, et al. Performance analysis of membrane separation for upgrading biogas to biomethane at small scale production sites. Biomass Bioenergy. 2019 Sep;128:105314.

26. Nolan T, Troy SM, Gilkinson S, Frost P, Xie S, Zhan X, et al. Economic analyses of pig manure treatment options in Ireland. Bioresour Technol. 2012 Feb 1;105:15–23.

27. Dennehy C, Lawlor PG, Gardiner GE, Jiang Y, Shalloo L, Zhan X. Stochastic modelling of the economic viability of on-farm co-digestion of pig manure and food waste in Ireland. Appl Energy. 2017 Nov 1;205:1528–37.

28. O'Connor S, Ehimen E, Pillai SC, Lyons G, Bartlett J. Economic and Environmental Analysis of Small-Scale Anaerobic Digestion Plants on Irish Dairy

Farms. Energies 2020, Vol 13, Page 637 [Internet]. 2020 Feb 3 [cited 2022 May 23];13(3):637. Available from: https://www.mdpi.com/1996-1073/13/3/637/htm

29. Wall DM, Allen E, Straccialini B, O'Kiely P, Murphy JD. The effect of trace element addition to mono-digestion of grass silage at high organic loading rates. Bioresour Technol. 2014 Nov;172:349–55.

30. Dillon E, Donnellan T, Moran B, Lennon J. Teagasc National Farm Survey 2021 [Internet]. 2022 [cited 2023 Aug 14]. Available from: https://www.teagasc.ie/media/website/publications/2022/Teagasc-National-Farm-Survey-2021.pdf

31. Hennessy T, Buckley C, Cushion M. teagasc. 2011 [cited 2022 Mar 10]. National farm survey of manure application and storage practices on Irish farms. Available from: https://www.teagasc.ie/media/website/publications/2011/TeagascNationalFarmSurveyOfManureApplication.pdf

32. Buckley C, Moran B, Donnellan T. Teagasc National Farm Survey A Report on Bovine Manure Management, Application and Storage Practices in Ireland Rural Economy and Development Programme.

33. Teagasc. Grass10 - Grassland Management [Internet]. 2023 [cited 2023 Sep 6]. Available from: https://www.teagasc.ie/crops/grassland/grass10/

34. Liebetrau J, Clemens J, Cuhls C, Hafermann C. Methane emissions from biogas-producing facilities within the agricultural sector. Eng Life Sci [Internet]. 2010 [cited 2022 Dec 6];10(6):595–9. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/elsc.201000070?casa_token=McPVFCtGSxwAAAAA:igXy_XypY3X7X3k83pDalpwCqQE6zv-c3VWymWffITc3KOto6sIOjqFcvutf-zGQdfLQIVk6zzJfqQ

35. Van Den Oever AEM, Cardellini G, Sels BF, Messagie M. Life cycle environmental impacts of compressed biogas production through anaerobic digestion of manure and municipal organic waste. J Clean Prod. 2021 Jul 15;306:127156.

36. Wu B, Lin R, O'Shea R, Deng C, Rajendran K, Murphy JD. Production of advanced fuels through integration of biological, thermo-chemical and power to gas

technologies in a circular cascading bio-based system. Renewable and Sustainable Energy Reviews. 2021 Jan 1;135:110371.

37. O'Shea R, Wall DM, Kilgallon I, Browne JD, Murphy JD. Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region. Appl Energy. 2017 Feb 15;188:237–56.

38. O'Connor S, Ehimen E, Pillai SC, Black A, Tormey D, Bartlett J. Biogas production from small-scale anaerobic digestion plants on European farms. Renewable and Sustainable Energy Reviews. 2021 Apr 1;139:110580.

39. Villarroel-Schneider J, Mainali B, Martí-Herrero J, Malmquist A, Martin A, Alejo L. Biogas based polygeneration plant options utilizing dairy farms waste: A Bolivian case. Sustainable Energy Technologies and Assessments. 2020 Feb 1;37:100571.

40. Bauer F, Hulteberg C, Persson T, Tamm D. Biogas upgrading-Review of commercial technologies; Biogasuppgradering-Granskning av kommersiella tekniker. 2013 [cited 2022 Jun 15]; Available from: https://www.osti.gov/etdeweb/biblio/22090519

41. IEA Bioenergy Task 37. Pioneering biogas farming in Central Finland. Farm scale biogas plant produces vehicle fuel, heat, electricity and bio-fertiliser [Internet]. 2012 [cited 2022 Jun 16]. Available from: https://www.ieabioenergy.com/blog/publications/pioneering-biogas-farming-in-central-finland/

42. Sun Q, Li H, Yan J, Liu L, Yu Z, Yu X. Selection of appropriate biogas upgrading technology-a review of biogas cleaning, upgrading and utilisation. Renewable and Sustainable Energy Reviews. 2015 Nov 1;51:521–32.

43. Deng C, Lin R, Kang X, Wu B, O'Shea R, Murphy JD. Improving gaseous biofuel yield from seaweed through a cascading circular bioenergy system integrating anaerobic digestion and pyrolysis. Renewable and Sustainable Energy Reviews. 2020 Aug 1;128:109895.

44. Power NM, Murphy JD. Which is the preferable transport fuel on a greenhouse gas basis; biomethane or ethanol? Biomass Bioenergy. 2009 Oct 1;33(10):1403–12.

45. Murphy JD, McKeogh E, Kiely G. Technical/economic/environmental analysis of biogas utilisation. Appl Energy. 2004 Apr 1;77(4):407–27.

46. O'Shea R, Wall DM, Kilgallon I, Browne JD, Murphy JD. Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region. Appl Energy. 2017 Feb 15;188:237–56.

47. Ó Céileachair D. SNAP input parameters and results [Internet]. Vol. 1. Mendeley Data; 2023 [cited 2023 Oct 23]. Available from: https://data.mendeley.com/datasets/5vkjkh8c6z/1

48. Gas Networks Ireland. Code of Operations [Internet]. 2023 [cited 2023 Oct 23]. Available from: https://www.gasnetworks.ie/corporate/gas-regulation/service-for-suppliers/code-of-operations/

49. CheCalc. 2023. [cited 2023 Oct 24]. Reciprocating Compressor Calculation. Available from: https://checalc.com/calc/compress.html

50. Grant Thornton. Renewable energy discount rate survey results-2018 [Internet]. 2019 [cited 2023 Jun 14]. Available from: https://www.grantthornton.co.uk/insights/renewable-energy-discount-rate-survey/

51. SEAI. Commercial / Industrial Fuels 01-Jan-23 Comparison of Energy Costs [Internet]. 2023 [cited 2024 Apr 1]. Available from: www.seai.ie/data-and-insights/seai-statistics/key-publications

52. The cost of producing home-grown feeds - Teagasc | Agriculture and Food Development Authority [Internet]. [cited 2022 Sep 20]. Available from: https://www.teagasc.ie/animals/beef/grange/beef2022-open-day/the-cost-of-producing-home-grown-feeds--/

53. EIRGRID. Renewable Electricity Support Scheme 1 RESS 1 Final Auction Results [Internet]. 2020 [cited 2022 Jul 1]. Available from: https://www.eirgridgroup.com/site-files/library/EirGrid/207158-EirGrid-Renewable-Energy-Scheme-LR5.pdf

54. Bruton T. A Guide to District Heating in Ireland [Internet]. 2016 [cited 2022 Sep 20]. Available from: https://www.seai.ie/publications/2016_RDD_79._Guide_District_Heating_Irl_-_CODEMA.pdf

55. Barsanti L, Gualtieri P. Is exploitation of microalgae economically and energetically sustainable? Algal Res. 2018 Apr;31:107–15.

56. Bose A, O'Shea R, Lin R, Murphy JD. A perspective on novel cascading algal biomethane biorefinery systems. Bioresour Technol. 2020 May;304:123027.

57. SEAI. Prices - Energy Statistics In Ireland [Internet]. 2022 [cited 2022 Aug 12]. Available from: https://www.seai.ie/data-and-insights/seai-statistics/key-statistics/prices/

58. Gas Network Ireland. GNI Transmission Tariffs for the Gas Year 2023/24 [Internet]. 2024 [cited 2024 Apr 1]. Available from: https://www.gasnetworks.ie/docs/corporate/gas-regulation/Current-Tariffs-2023-24.pdf

59. Nolan T, Troy SM, Gilkinson S, Frost P, Xie S, Zhan X, et al. Economic analyses of pig manure treatment options in Ireland. Bioresour Technol. 2012 Feb 1;105:15–23.

60. Rajendran K, Browne JD, Murphy JD. What is the level of incentivisation required for biomethane upgrading technologies with carbon capture and reuse? Renew Energy. 2019 Apr 1;133:951–63.

61. Budzianowski WM, Wylock CE, Marciniak PA. Power requirements of biogas upgrading by water scrubbing and biomethane compression: Comparative analysis of various plant configurations. Energy Convers Manag. 2017 Jun;141:2–19.

7 Conclusions and recommendations

7.1 Conclusions

This thesis investigated the financial and environmental feasibility of on-farm anaerobic digestion (AD) systems in Ireland as a means of generating renewable energy and reducing emissions from the agricultural sector. It explores various end-uses of biogas, including heat, electricity, and biomethane, derived from agricultural feedstocks as sustainable alternatives to fossil fuels. The considerations that are studied in this work include: the system boundaries used to assess the economic and environmental impact of on-farm AD; the assessment of the mitigation potential of on-farm AD based on different biogas end-uses through an enviro-economic tool; the influence of external variables over the uncertainty on the abatement cost and potential of on-farm AD; and the impact of novel technologies and the implementation of biogas pipelines can have on the economic viability of on-farm AD systems. Based on these considerations, eight research objectives were raised in section 1.2. These objectives are now answered below:

i. To comprehensively assess the financial and environmental viability of on-farm AD, it is imperative to consider additional inputs and outputs within the system boundary beyond energy sales alone. This approach allows for a more reasonable estimation of on-farm AD viability. Such considerations include factoring the income generated from the sale of co-products and biofertilisers produced during the AD process, as well as accounting for emissions reductions resulting from the use of digestate as an organic biofertiliser, displacing the need for chemical fertilisers.

ii. The mitigation potential of on-farm AD can be heavily influenced by the scale and processes considered within the analysis. A single scenario may not adequately capture the diverse variables present in different AD systems, including variation in scale, type of system, or energy output. The assessment of on-farm AD at two different scales, small and medium, revealed that the abatement cost can vary from -117 € tCO_{2eq}^{-1} to +79 € tCO_{2eq}^{-1} clearly indicating that the variables selected for the study have a significant influence on the results.

iii. Four different configurations for utilising biogas were assessed: heat generation with a boiler, heat and electricity generation with a combined heat and power (CHP) generation, biogas upgrading to biomethane for heat or transport fuel, and biogas upgrading combined with CHP. Small-scale AD systems may not be financially feasible given current feedstock and energy costs. Heat generation with a boiler was deemed viable for farms with a minimum herd size of 185 cows, while biogas upgrading was found to be the least financially viable option due to high capital and operational costs.

iv. The abatement cost curve revealed a wide range of mitigation cost which varied significantly, from -7 € tCO_{2eq}^{-1} to 816 € tCO_{2eq}^{-1} across different scales, considering various biogas end-uses. Mitigation costs can be notably affected by minor alterations in input variables or adjustments to the system boundary which can significantly impact both the financial and environmental performance of AD systems. This shows the importance of comprehensive assessments and flexible methodologies in accurately evaluating the viability and effectiveness of on-farm AD systems.

v. The efficiency of the AD process proved pivotal in determining abatement costs, impacting both financial and environmental outcomes across biogas end-uses. Farm conditions, particularly the yield of grass silage and required synthetic fertiliser, also significantly influenced system sustainability and financial viability. Increasing the proportion of grass silage positively correlated with plant profitability due to heightened methane yield.

vi. Heat and electricity production from on-farm AD systems exhibited lower uncertainty in abatement costs, given anticipated rate increases in support schemes aligned with Ireland's renewable energy investments. Conversely, biomethane production displayed higher uncertainty due to fluctuating energy prices stemming from recent geopolitical events. Small-scale upgrading in particular had a 50% probability of having abatement cost between 107 to 464 € tCO_{2eq}^{-1}. Small-scale on-farm AD systems may face diseconomies of scale in biomethane production, additional incentives will be required to foster farmer participation in the biomethane market.

vii. The integration of microbial electrolysis cell (MEC) technology into AD systems offers a clear advantage by making small-scale upgrading more economically feasible. This technology can increase the revenues of small-scale upgrading up to 91% with only a 41% increase in operational cost. However, the high operational and capital costs of small-scale upgrading may limit the investment available for this innovative technology.

viii. Connecting on-farm AD systems to a centralised upgrading facility presents a promising alternative for optimising logistics in delivering biogas. This approach significantly reduces the required investment by almost 21.5% for AD systems compared to on-site upgrading systems.

7.2 Research implications and recommendations

Drawing from the conclusions outlined in section 7.1 and aligning with the SFI MaREI research centre's three impact priorities of 1) informing policy, 2) supporting industry, and 3) empowering society, the subsequent recommendations are proposed:

7.2.1 Policy

The findings of this thesis demonstrate the need for significant government support to enhance the financial viability of small-scale, on-farm anaerobic digestion (AD) systems for biomethane production, particularly concerning policies related to energy prices and feedstock costs. The Irish government currently offers two schemes for renewable energy projects: the Support Scheme for Renewable Heat (SSRH), which provides a tariff of 29.5 € MWh^{-1} of energy produced, and the Renewable Electricity Support Scheme (RESS), offering a tariff of 74.08 € MWh^{-1} of energy produced.

As shown in the results of this thesis in chapter 4 and 5, these supports are sufficient to make on-farm AD systems with a boiler or a Combined Heat and Power (CHP) units financially viable, as these systems can apply the schemes. However, the results presented in Chapter 5, specifically the abatement cost curves, indicate that systems focused on biomethane production require additional support to become financially viable and attractive for farmers to integrate into their operations.

Schemes like the Renewable Transport Fuel Obligation (RTFO), which requires transport fuel suppliers in Ireland to ensure that 15% of the fuel volume on the market is sourced from renewable fuels, can provide additional income to farms producing biomethane. This income is generated through Biofuel Obligation Certificates (BOCs) when the biomethane is used as transport fuel. While this additional income can be beneficial, there is still a need to consider capital grants to reduce the investment cost of small-scale upgrading systems.

To formulate effective energy policies for biomethane production, it is crucial to gain a comprehensive understanding of the range of abatement cost values associated with on-farm anaerobic digestion (AD), taking into account the uncertainties inherent in different system scales and processes within the system boundary. In Ireland, policymakers have traditionally used marginal abatement cost curves (MACC) to assess the mitigation potential of AD and compare it with other agricultural decarbonization options. While these are useful for initial analyses, achieving a complete understanding of the factors affecting the viability of on-farm AD biomethane production requires consideration of all external variables influencing production costs.

Specifically, variables that impact the efficiency of the AD process in producing biomethane, as well as those affecting feedstock costs and energy prices (including the energy consumed and the selling price of biomethane), must be incorporated into abatement cost scenarios. This comprehensive approach is essential to enable a thorough comparison of all potential scenarios that could be integrated into small farms, thereby making small-scale upgrading systems viable.

7.2.2 Industry

The agricultural sector in Ireland currently contributes a significant 38.5% of total greenhouse gas emissions, presenting a considerable challenge in meeting the sectoral emission ceiling of 25% reduction. On-farm AD emerges as a potential solution, offering livestock farmers a means to mitigate emissions from animal wastes while simultaneously producing biobased fertilisers that can replace chemical fertilisers, thereby promoting carbon sequestration on land.

While biogas and biomethane production presents a promising diversification option for farmers, enabling them to own, operate, and supply feedstock to AD plants at a reasonable price is essential. The economic analysis conducted in this thesis revealed that the cost of grass silage as feedstock and current selling prices of energy rendered most small-scale AD to be not financially viable. Addressing this issue will require exploring options to reduce the cost of growing grass silage, such as integrating multi-species sward to lower fertilizer expenses or considering grass obtained as a by-product of landscape management from non-pasture areas as potential feedstock.

Furthermore, considering the biomethane strategy, this sector faces challenges and considerations associated with high investment costs for small-scale upgrading. Capital grants can help reduce the overall investment cost, but thorough communication with farmers will be essential to help them integrate these new technologies into their farms. The use of cooperatives might help unite farmers and assist them in managing these systems on their farms. Additionally, integrating industry, community, and farmers into the broader picture of the biomethane industry will be necessary to make the endeavor of producing the required 5.7 TWh of biomethane a reality.

For small-scale upgrading, this will also entail exploring new technologies that can reduce investment costs and increase efficiency in biomethane generation. This could integrate new technologies such as Microbial electrolysis cell units in the reactors to increase biomethane production. Furthemore, virtual pipelines, and physical pipelines can be integrated into small scale systems to facilitate transportation of the generated biogas or biomethane to the end user.

Finally, relying solely on biomethane sales as the main revenue source may prove insufficient to secure financial viability for small-scale production, necessitating additional revenue streams. These could include biorefinery approaches to convert digestate into high-value products or the integration of industries requiring high-temperature heat processes. Such industries could utilize biomethane as an immediate decarbonization solution without directly affecting their operations or incurring significant additional expenses.

7.2.3 Future research

As this thesis achieved to identified key economic and environmental parameters that need to be taken in consideration for the viability of on-farm AD, further research is recommended as follows:

i. This thesis demonstrates that overall, on-farm AD systems co-digesting slurry and surplus grass as feedstock can struggle financially in small-scale scenarios. The consideration of co-products or biorefineries approaches could increase the economic viability of these systems by considering other revenue streams.

ii. The solid and liquid fraction of digestate could also be considered as additional revenue stream to on-farm AD. This could involve the production of biochar, bio-oil and syngas through pyrolysis, or the cultivation of microalgae using the liquid fraction as culture medium to generate valuable chemicals or proteins. However, it would be required to take into consideration the required investment for additional equipment required and the overall increment in operational costs.

iii. All the relevant inputs and outputs for the abatement cost calculations should incorporate sensitivity analysis and uncertainty analysis to provide a more realistic assessment of on-farm AD systems.

iv. The overall capital cost used in this study was based in previous co-digestion systems of slurry and grass silage. A deeper analysis would require analysing with Irish developers the overall associated cost with installation and the applied cost that some equipment may have if it is imported from other countries.

v. Whilst the overall energy crop considered was focused on grass silage, other options could be considered as potential energy crop feedstocks to reduce the feedstock acquisition cost for on-farm AD systems. One potential option could involve multi-species swards which require less fertiliser and can increase grass output while decreasing emissions. Further research is required to evaluate the feasibility of co-digestion with slurry, thus expanding the scope of potential feedstock options for enhanced sustainability and economic viability of on-farm AD.

vi. Potential improvements to small-scale upgrading technologies could be further researched to reduce the overall high cost of upgrading for small-scale on-farm AD.

vii. Multicriteria decision analysis could be integrated into the enviro-economic tool developed to provide a cost-effective method for assessing scenarios, allowing users to prioritise either financial or environmental performance based on their preferences.

viii. Further research should assess the implementation cost of microbial electrolysis cell in farm size digestors to assess the effect on the production of biomethane and the energy efficiency against the laboratory results.

ix. Performing a comprehensive techno-economic analysis, coupled with scenario analyses could help to explore different connection points and optimising biogas flow rates. This approach could minimise power consumption in compression further enhances the economic feasibility of biogas pipeline networks.

Appendices

Appendix A

Appendix A.1

Table A-1 Variability of system boundary in previous literature for TEA and LCA analyses of on-farm AD systems.

Areas of Focus	Associated Processes	TEA															TEA + LCA					LCA		
		(1)*	(2)*	(3)*	(4)*	(5)*	(6)*	(7)*	(8)*	(9)*	(10)*	(11)*	(12)*	(13)*	(14)*	(15)*	(16)*	(17)*	(18)*	(19)*	(20)	(21)	(22)	(23)
Feedstock production / Acquisition and Transport	Feedstock Acquisition	X	X	X	X	X	X			X					X	X	X	X	X	X	X	X		
	Feedstock Handling	X	X			X	X			X							X	X	X	X	X	X		X
	Feedstock Storage									X						X	X		X	X	X	X	X	X
	Transportation by Land or Pipe	X								X			X	X		X	X	X	X	X	X	X		X
	Farm Labour						X												X		X			
Pre-treatment and Anaerobic Digestion	Construction of Anaerobic Digester	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Purchase of CHP unit	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Acquisition of Heat Exchange and Water Pumps	X	X	X		X	X			X			X	X	X	X	X	X		X				
	Maintenance and Repair of the system	X	X	X		X	X	X		X	X	X	X	X	X	X	X	X	X	X	X			
	Insurance		X	X					X	X	X				X				X	X	X			
	Plant Labour		X	X		X	X		X	X	X							X	X	X	X			
Biogas Post Processing / Utilisation and coproduct handling	Connection to Gas Grid or Electricity Grid				X								X	X		X								X
	Purchase of Gas Purification Unit				X							X												X
	Operation of Upgrading System				X							X												X
	Selling of electricity and/or heat generated	X	X	X	X	X	X	X		X	X		X	X	X	X	X		X	X	X	X	X	X
	Selling of Biomethane produced				X				X			X		X										
	Land spreading of Digestate	X	X	X	X	X				X						X	X		X			X	X	
	Treatment of Digestate					X															X		X	
	Selling of Digestate as Biofertiliser					X	X				X				X		X					X	X	

Studies with * were included for review as more insight was provided on the processes considered in the system boundary and included at least one process in each of the areas of focus of the AD process. Furthermore, the studies selected contain a clear breakdown of the processes included in the CapEx, OpEx and Revenues.

[1] Khan EU, Mainali B, Martin A, Silveira S. Techno-economic analysis of small scale biogas based polygeneration systems: Bangladesh case study. Sustainable Energy Technologies and Assessments 2014;7:68–78. https://doi.org/10.1016/j.seta.2014.03.004.

[2] Imeni SM, Puy N, Ovejero J, Busquets AM, Bartroli J, Pelaz L, et al. Techno-Economic Assessment of Anaerobic Co-digestion of Cattle Manure and Wheat Straw (Raw and Pre-treated) at Small to Medium Dairy Cattle Farms. Waste Biomass Valor 2020;11:4035–51. https://doi.org/10.1007/s12649-019-00728-4.

[3] Mostafa Imeni S, Pelaz L, Corchado-Lopo C, Maria Busquets A, Ponsá S, Colón J. Techno-economic assessment of anaerobic co-digestion of livestock manure and cheese whey (Cow, Goat & Sheep) at small to medium dairy farms. Bioresource Technology 2019;291:121872. https://doi.org/10.1016/j.biortech.2019.121872.

[4] Perta ES di, Cervelli E, Campagna MP di, Pindozzi S. From biogas to biomethane: Techno-economic analysis of an anaerobic digestion power plant in a cattle/buffalo farm in central Italy. Journal of Agricultural Engineering 2019;50. https://doi.org/10.4081/jae.2019.939.

[5] Villarroel-Schneider J, Mainali B, Martí-Herrero J, Malmquist A, Martin A, Alejo L. Biogas based polygeneration plant options utilizing dairy farms waste: A Bolivian case. Sustainable Energy Technologies and Assessments 2020;37:100571. https://doi.org/10.1016/j.seta.2019.100571.

[6] Wresta A, Andriani D, Saepudin A, Sudibyo H. Economic Analysis of Cow Manure Biogas as Energy Source for Electricity Power Generation in Small Scale Ranch. Energy Procedia 2015;68:122–31. https://doi.org/10.1016/j.egypro.2015.03.240.

[7] Teymoori Hamzehkolaei F, Amjady N. A techno-economic assessment for replacement of conventional fossil fuel based technologies in animal farms with biogas fueled CHP units. Renewable Energy 2018;118:602–14. https://doi.org/10.1016/j.renene.2017.11.054.

[8] González-Arias J, Baena-Moreno FM, Gonzalez-Castaño M, Arellano-García H, Lichtfouse E, Zhang Z. Unprofitability of small biogas plants without subsidies in the Brandenburg region. Environ Chem Lett 2021;19:1823–9. https://doi.org/10.1007/s10311-020-01175-7.

[9] Blumenstein B, Siegmeier T, Möller D. Economics of anaerobic digestion in organic agriculture: Between system constraints and policy regulations. Biomass and Bioenergy 2016;86:105–19. https://doi.org/10.1016/j.biombioe.2016.01.015.

[10] Jarrar L, Ayadi O, Al Asfar J. Techno-economic Aspects of Electricity Generation from a Farm BasedBiogas Plant. Journal of Sustainable Development of Energy, Water and Environment Systems 2020;8:476–92. https://doi.org/10.13044/j.sdewes.d7.0302.

[11] Oreggioni GD, Luberti M, Reilly M, Kirby ME, Toop T, Theodorou M, et al. Techno-economic analysis of bio-methane production from agriculture and food industry waste. Energy Procedia 2017;123:81–8. https://doi.org/10.1016/j.egypro.2017.07.252.

[12] Oreggioni GD, Gowreesunker BL, Tassou SA, Bianchi G, Reilly M, Kirby ME, et al. Potential for Energy Production from Farm Wastes Using Anaerobic Digestion in the UK: An Economic Comparison of Different Size Plants. Energies 2017;10:1396. http://dx.doi.org.ucc.idm.oclc.org/10.3390/en10091396.

[13] Oreggioni GD, Luberti M, Tassou SA. Agricultural greenhouse CO2 utilization in anaerobic-digestion-based biomethane production plants: A techno-economic and environmental assessment and comparison with CO2 geological storage. Applied Energy 2019;242:1753–66. https://doi.org/10.1016/j.apenergy.2019.03.045.

[14] Tan JB, Jamali NS, Tan WE, Che Man H, Zainal Abidin Z. Techno-Economic Assessment of On-Farm Anaerobic Digestion System Using Attached-Biofilm Reactor in the Dairy Industry. Sustainability 2021;13:2063. https://doi.org/10.3390/su13042063.

[15] Abdul-Salam Y, Ehlers M-H, Harnmeijer J. Anaerobic Digestion of Feedstock Grown on Marginal Land: Break-Even Electricity Prices. Energies 2017;10:1416. http://dx.doi.org.ucc.idm.oclc.org/10.3390/en10091416.

[16] Torquati B, Venanzi S, Ciani A, Diotallevi F, Tamburi V. Environmental Sustainability and Economic Benefits of Dairy Farm Biogas Energy Production: A Case Study in Umbria. Sustainability 2014;6:6696–713. https://doi.org/10.3390/su6106696.

[17] Lopes TF, Carvalheiro F, Duarte LC, Gírio F, Quintero JA, Aroca G. Techno-economic and life-cycle assessments of small-scale biorefineries for isobutene and xylo-oligosaccharides production: a comparative study in Portugal and Chile. Biofuels, Bioproducts and Biorefining 2019;13:1321–32. https://doi.org/10.1002/bbb.2036.

[18] O'Connor S, Ehimen E, Pillai SC, Black A, Tormey D, Bartlett J. Biogas production from small-scale anaerobic digestion plants on European farms. Renewable and Sustainable Energy Reviews 2021;139:110580. https://doi.org/10.1016/j.rser.2020.110580.

[19] Aui A, Li W, Wright MM. Techno-economic and life cycle analysis of a farm-scale anaerobic digestion plant in Iowa. Waste Management 2019;89:154–64. https://doi.org/10.1016/j.wasman.2019.04.013.

[20] Croxatto Vega G, Voogt J, Sohn J, Birkved M, Olsen SI. Assessing New Biotechnologies by Combining TEA and TM-LCA for an Efficient Use of Biomass Resources. Sustainability 2020;12:3676. https://doi.org/10.3390/su12093676.

[21] Nayal FS, Mammadov A, Ciliz N. Environmental assessment of energy generation from agricultural and farm waste through anaerobic digestion. Journal of Environmental Management 2016;184:389–99. https://doi.org/10.1016/j.jenvman.2016.09.058.

[22] Pardo G, Moral R, del Prado A. SIMSWASTE-AD - A modelling framework for the environmental assessment of agricultural waste management strategies: Anaerobic digestion. Science of The Total Environment 2017;574:806–17. https://doi.org/10.1016/j.scitotenv.2016.09.096.

[23] Adams PWR, McManus MC. Characterisation and variability of greenhouse gas emissions from biomethane production via anaerobic digestion of maize. Journal of Cleaner Production 2019;218:529–42. https://doi.org/10.1016/j.jclepro.2018.12.232.

Appendix B

Appendix B.1

The total feedstock resource of both cattle slurry (R_1^{CS}) and grass silage (R_2^{GS}) was calculated in terms of wet weight tonnes (t_{wwt}) per year.

Equation B1 Cattle Slurry resource per year by type of livestock

$$R_1^{CS}\left(\frac{t_{wwt}}{a}\right) = N_{livestock_\theta} * Y_{livestock_\theta} + \cdots + N_{livestock_n} * Y_{livestock_n}$$

In Equation B1, the Cattle Slurry resource (R_1^{CS}- t_{wwt} a^{-1}) was calculated based on the annual slurry production per head of livestock ($N_{livestock\vartheta}$) and the total number of livestock ($Y_{livestock\vartheta}$) on the farm considering that the slurry was collected indoors and stored in a slurry tank. As there can be different types of cattle livestock ($N_{livestock\vartheta}$) on a dairy farm (dairy cows, suckler cows, and cattle) the enviro-economic tool developed includes preloaded information on the slurry production per head of bovine livestock which can range between 0.08 to 0.33 m^3 of slurry per week based on the national farm survey of manure application and storage practices in Irish farms (1). For the scenarios assessed, it was assumed that the herd consisted of adult dairy cows with a production of 0.33 m^3 of slurry per week. The annual slurry production per head of livestock ($Y_{livestock\vartheta}$) was then calculated based on the number of weeks that each head of livestock will be housed indoors to facilitate slurry collection. In an Irish context, this amount of time can range between 16 to 22 weeks based on the required minimum storage capacity for bovine livestock manure based on the farm location in Ireland, as part of the Good Agricultural Practice for Protection of Waters (GAP) (2). For the analysis, a period of 18 weeks indoors was assumed for the livestock based on the nitrate's directive of the GAP regulation in Ireland (Table B-1). It is assumed in this work that the specific gravity of slurry is 1.

The resource of grass silage (R_2^{GS}) available for use in AD was assumed to be the excess grass silage (surplus to livestock requirements) harvested at the farm under assessment. The yield of the grass (tonnes of dry matter (tDM) per hectare (ha) per annum) varies according to the specific region within Ireland but typically for fertile farmland ranges from 11 to 13 tDM ha^{-1} per annum (3–7). A value of 7 tDM ha^{-1} for first cut and 4 tDM ha^{-1} for second cut per annum was selected for the yield of the hypothetical farms under analysis (8,9).

Equation B2 Silage resource per year including first and second cut.

$$R_2^{GS}\left(\frac{\mathrm{t_{wwt}}}{\mathrm{a}}\right) = \frac{A_{grass} * Y_{FC}^{Silage}}{TS_{FC}/100} + \frac{A_{grass} * Y_{SC}^{Silage}}{TS_{SC}/100}$$

In Equation B2, the grass silage resource (R_2^{GS}, t_{wwt} a^{-1}) was calculated considering the first and second cuts of grass on the farm that will be allocated for its use as feedstock for the AD process. This was based on the area of land used to produce silage (A_{grass}, ha) for each of the four hypothetical farm sizes and the yield of grass for *the first and second cuts* (Y_{FC}^{Silage},Y_{SC}^{Silage}, tDM/ha/a). These values are divided by the total solids (TS_{FC} and TS_{SC}) content (expressed as a decimal) of each grass cut as per Table B-2 to obtain the total wet tonnage of grass silage.

Table B-1 Minimum Storage capacity for bovine livestock manure in Ireland.

Zone	Counties	Weeks
A	Carlow, Cork, Dublin, Kildare, Kilkenny, Laois, Offaly, Tipperary, Waterford, Wexford, Wicklow	16
B	Clare, Galway, Kerry, Limerick, Longford, Louth, Mayo, Meath, Roscommon, Sligo, Westmeath	18
C	Donegal, Leitrim, Cavan*, Monaghan*.	20 or 22*

*For the regions of Cavan and Monaghan, the minimum storage period was designated as 22 weeks as Donegal and Leitrim have higher water quality and lower agricultural production.

Appendix B.2

The volumetric biogas production (V_{AD}) from the co-digestion of grass silage and cattle slurry was then calculated in cubic metres per annum ($m^3\ a^{-1}$) based on the volatile solids content of the feedstock mixture (which include the cattle slurry (VS_{CS}), grass silage first cut ($VS_{GS^{FC}}$) and grass silage second cut ($VS_{GS^{SC}}$)), the specific methane yield ($LCH_4\ kgVS^{-1}$) of the cattle slurry (SMY_{CS}), grass silage first cut ($SMY_{GS^{FC}}$), and the second cut ($SMY_{GS^{SC}}$) (Equation B3), and the methane content of the biogas from each feedstock used in the mixture as per Table B-2. The methane (CH_4) content of each feedstock ($\%CH_{4_{CS}}$, $\%CH_{4_{GS^{FC}}}$, $\%CH_{4_{GS^{SC}}}$) was calculated based on the molar portion of methane and carbon dioxide in the biogas obtained by the Buswell Equation (Equation B4).

Equation B3 Biogas production based on the methane yield of co-digestion of cattle slurry (CS) and grass silage (GS).

$$V_{AD}\left(\frac{m^3}{a}\right) = \frac{(R_1^{CS} * VS_{CS}) * SMY_{CS}}{\frac{\%CH_{4_{CS}}}{100}} + \frac{\left(R_2^{GS^{FC}} * VS_{GS^{FC}}\right) * SMY_{GS^{FC}}}{\frac{\%CH_{4_{GS^{FC}}}}{100}} + \frac{\left(R_2^{GS^{SC}} * VS_{GS^{SC}}\right) * SMY_{GS^{SC}}}{\frac{\%CH_{4_{GS^{SC}}}}{100}}$$

The gross energy output of the AD process (EO_{AD}) in units of MJ/a was then calculated based on the overall biogas production (V_{AD}- $m^3\ a^{-1}$) considering an organic loading rate (OLR) of 2.5 kgVS m^{-3} per day under mesophilic conditions (40ºC), and a calorific value for methane (cv_{CH_4}) of 35.7 MJ $Nm^3CH_4^{-1}$ assuming the lower heating value (LHV) of methane as 50 MJ kg^{-1} and the density of methane as 0.714 kg m^{-3} at STP (0 Cº, 1 atm).

Table B-2 Characteristics of slurry on Irish farms collected when livestock are indoors. Adapted from Allen et al. (10).

Slurry Type	Total Solids (TS) (%wwt)	Volatile Solids (VS) (%wwt)	Ash (%wwt)	Volatile Solids/Total Solids (%)	Specific Methane Yield (LCH_4 $kgVS^{-1}$)	Nitrogen in Total Solids (%)
Summer Dairy Slurry	8.8%	6.7%	2.1%	76.5%	239.4	2.2%
Autumn Dairy Slurry	6.5%	5.1%	1.4%	78.5%	175.5	2.0%
Dairy Slurry (Dec-Jan)	7.1%	5.8%	1.4%	80.9%	199.8	2.5%
Dairy Slurry (Feb-Apr)	9.1%	6.6%	2.5%	72.1%	214.0	2.2%
Slurry (Dairy Heifers)	7.8%	5.5%	2.3%	70.3%	136.1	1.7%
Slurry (Beef)	8.4%	6.8%	1.7%	80.1%	310.8	2.6%

Table B-3 Characteristics of grass silage harvested at different stages across three regions of Ireland (North, Midland, and South). Adapted from Allen et al. (10).

Silage Type	Total Solids (%wwt)	Volatile Solids (%wwt)	Ash (%wwt)	Volatile Solids /Total Solids (%)	Specific Methane Yield (LCH_4 $kgVS^{-1}$)	Nitrogen in Total Solids (%)
Silage Bales (1st cut)	16.8%	15.3%	1.5%	91.1%	432.9	1.5%
Silage Bales (2nd cut)	17.4%	15.9%	1.5%	91.6%	428.4	1.7%
1st Cut Grass Silage (Midlands)	29.3%	26.8%	2.4%	91.7%	399.6	1.7%
Late Cut Grass Silage (Midlands)	17.9%	16.4%	1.4%	92.0%	392.6	1.1%
1st Cut Grass Silage (North)	16.8%	15.3%	1.5%	91.1%	432.9	1.7%
1st Cut Grass Silage (South)	17.4%	15.9%	1.5%	91.6%	428.4	1.0%

Equation B4 Buswell equation to calculate the methane content based on elemental composition data for a substrate.

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right) H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right) CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right) CO_2$$

Appendix B.3

To calculate the thermal demand of the AD process (TD_{AD}) in MJ a^{-1}, different thermal demands were considered for the energy balance (Equation B5). These include the heat required for substrate heating (SH_{AD}), heat loss to the environment (HL_E), and heat loss through evaporation inside the digester (HL_{WER}).

Equation B5 Net thermal demand of the AD process.

$$TD_{AD}\left(\frac{\text{MJ}}{\text{a}}\right) = (SH_{AD} + HL_E + HL_{WER})$$

To determine the energy in MJ/a to heat the feedstock mixture (SH_{AD}), Equation B6 was used which considers the temperature in C⁰ required to heat the feedstock mixture from the inlet temperature (T_{In}) to the one specified by the user for the AD process (T_{AD}), the water content of the mixture (T^{WC_R} - kg a^{-1}) and the specific heat capacity of water (C_pH_2O: $4.184\frac{kJ}{kg\ °C}$) (11).

Equation B6 Thermal demand for substrate heating for the AD process.

$$SH_{AD}\left(\frac{\text{MJ}}{\text{a}}\right) = \left(\left(T^{WC_R} * 1000 * C_pH_2O * (T_{AD} - T_{In})\right)/1000\right)$$

For the heat loss to the environment (HL_E), the thermal demand in MJ/a comes from the fabric heat loss which is calculated based on the surface area of the AD reactor and the external temperature (Equation B7). The heat transfer value of the material (U_{Tank}-W m^2C^{o-1}) determines the thermal energy lost through the reactor fabric based on the difference between the temperature in C⁰ of the AD tank (T_{AD}) and the external air temperature (T_{Out}) (12). For the surface area in contact with the external air the tool assumes the reactor to be cylindrical and that the areas in contact in m^2 with the external environment are the walls (A_{Wall}), top (A_{Top}), and bottom of the reactor (A_{Base}). For the external air temperature (T_{Out}), the average dry bulb temperature in C⁰ for Cork, Ireland based on the ASHRAE climatic design conditions for the years 2009, 2013, and 2017 was used (13).

Equation B7 Thermal demand due to fabric heat loss for the AD process.

$$HL_E\left(\frac{\text{MJ}}{\text{a}}\right) = \frac{\left(U_{Tank}A_{Wall}(T_{AD} - T_{Out}) + U_{Tank}A_{Top}(T_{AD} - T_{Out}) + U_{Tank}A_{Base}(T_{AD} - T_{Out})\right)}{1 * 10^6}$$

Finally, for the heat loss through evaporation (HL_{WER}), the thermal demand in MJ/a was calculated based on the energy required to evaporate the water inside the reactor (Equation B8). This assumes that the biogas is saturated with water and uses the mass of water vapour in kg contained in the biogas ($m_{water_{biogas}}$) which is calculated using the specific enthalpy of water evaporation at the temperature set for the AD reactor (h_{we}: 2260 $\frac{KJ}{Kg}$) (12).

Equation B8 Thermal demand for substrate heating for the AD process.

$$HL_{WER}\left(\frac{\text{MJ}}{\text{a}}\right) = \left(m_{water_{biogas}} * h_{we}\right)/1000$$

To obtain the mass of water vapour (kg) contained in the biogas, it is assumed that the water vapour behaves as an ideal gas within the biogas mixture (V_{AD} - m^3) based on the saturation pressure of the water vapour (p_{sat}- kPa) within the reactor, the temperature set for the reactor in C⁰ (T_{AD}) and using the universal gas constant of water (R_{water}: 0.461 $\frac{kPa\ m^3}{Kg\ K}$) as shown in Equation B9 (12).

Equation B9 Calculation for the mass of water vapour in the biogas for the AD process.

$$m_{Water_{biogas}}\left(\frac{\text{kg}}{\text{a}}\right) = p_{sat}\cdot\frac{V_{AD}}{R_{water} * (T_{AD} + 273.15)}$$

The saturation pressure of the water vapour was obtained as by ASHRAE fundamentals (Equation B10), by using the temperature set for the reactor in kelvin (T_{AD_K}) and the values set for the coefficients as shown in Table B-4.

Equation B10 Saturation of the water vapour of the biogas.

$$p_{sat} = e^{\left(\frac{C_1}{T_{AD_K}}+C_2+C_3T_{AD_K}+C_4T_{AD_K}{}^2+C_5T_{AD_K}{}^3+C_6\ln(T_{AD_K})\right)}$$

Table B-4 Coefficients used in the calculation of the saturation vapour pressure of water.

Coefficient	**Value**
C_1	-5.8002206E+03
C_2	1.3914993E+00
C_3	-4.8640239E-02
C_4	4.1764768E-05
C_5	-1.4452093E-08
C_6	6.5459673E+00

Appendix B.4

The required size of the boiler (kW_{th}) for each scenario was determined based on the overall gross heat output calculated from the AD gross energy output (EO_{AD}) and the boiler efficiency (η_{Boiler}) and the annual operating hours of the system (OLD) based on a total operating time of 8250 hours (94% availability) as per Equation B11. It is also assumed that the electric demand of the AD process (ED_{AD} – kWh a^{-1}) will be satisfied using electricity from the electricity grid.

Equation B11 Boiler configuration: Boiler size.

$$Boiler\ Size(kW_{th}) = \frac{(EO_{AD} * \eta_{Boiler})/3.6}{OLD}$$

The size of the CHP required for each scenario was calculated based on the overall gross electric output and the gross heat output from the unit. This was calculated from the AD gross energy output (EO_{AD}), the CHP electric efficiency (η_{ECHP}), the CHP heat efficiency (η_{TCHP}) and the OLD described in section 4.2.3 was used to obtain the CHP size in kW_{el} (Equation B12) and in kW_{th} (Equation B13).

Equation B12 Calculations for CHP size (kW_{el}) based on the final gross electric output of the process.

$$CHP\ Size\ (kW_{el}) = \frac{\left((EO_{AD} * \eta_{ECHP})/3.6\right)}{OLD}$$

Equation B13 Calculations for CHP size (kW_{th}) based on the final gross electric output of the process.

$$CHP\ Size\ (kW_{th}) = \frac{\left((EO_{AD} * \eta_{TCHP})/3.6\right)}{OLD}$$

Appendix B.5

Table B-5 Common biogas upgrading technologies and their technical features.

Biogas Upgrading Technology	Methane Recovery (V/V %)	Methane Slip (%V)	Electrical Demand (kWh m^{-3} biogas)	Thermal Demand (kWh m^{-3} biogas)	Biomethane Purity	Source
Water Scrubbing	94%	6.0%	0.45	-	97%	(14–16)
Pressure Swing Adsorption	91%	9.0%	0.335	-	98%	(15–17)
Chemical/Amine Scrubbing	90%	10.0%	0.415	0.55	96%	(15–17)
Membrane Separation	99%	0.105%	0.31	-	99%	(15–17)

Appendix B.6

The electrical demand (ED_{UP}) and thermal demand (TD_{UP}) were calculated in kWh/a based on the amount of biogas upgraded (V_{AD}-m^3 a^{-1}) using an specific electricity demand of 0.45 kWh m^{-3} biogas (SE_{UP}) and a thermal demand (TD_{UP}) of 0 kWh m^{-3} biogas for water scrubbing (Table B-5) as per Equation B14 and Equation B15.

Equation B14 Electrical demand of the biogas upgrading process.

$$ED_{UP}\left(\frac{kWh}{a}\right) = V_{AD} * SE_{UP}$$

Equation B15 Thermal demand of the biogas upgrading process.

$$TD_{UP}\left(\frac{kWh}{a}\right) = V_{AD} * SH_{UP}$$

It is assumed that to cover the thermal demand of the AD and upgrading process (TD_{AD}, TD_{UP}- kWh a^{-1}) natural gas would be combusted in a boiler to provide the thermal energy for the system. Different fuel types (natural gas, oil, and wood chips) can be used in a boiler to produce heat, but the efficiency of the boiler (η_{Boiler}) will change based on the selected fuel (Table B-6). For the initial analysis, natural gas was selected to generate heat, but different types of fuels were compared to assess the emission and cost impact that each fuel has on the configuration.

Table B-6 Boiler efficiency for different types of fuels.

Boiler Type	Efficiency	Source
Natural Gas	90%	(18,19)
Oil	85%	(20)
Wood chips	85%	(21)

Taking consideration of the parasitic energy demand of the upgrading process (ED_{UP} and TD_{UP}- kWh a^{-1}), the energy efficiency of the biogas upgrading process (η_{UP}) was calculated as shown in Equation B16 based on the overall energy output of the upgrading process (EO_{UP} – kWh a^{-1}) and the overall energy output of the AD process (EO_{AD}- MJ a^{-1}) .

Equation B16 Energy efficiency of the biogas upgrading process.

$$\eta_{UP}\ (\%) = \frac{EO_{UP}}{\left(\frac{EO_{AD}}{3.6}\right) + \ (ED_{UP} + TD_{UP})} * 100$$

Appendix B.7

As part of the calculations for the CAPEX of AD systems for the different configurations, AD systems previously installed in Ireland were used to calculate an approximate value based on the capital cost reported and feedstock processed. Based on a previous assessed system in Ireland, the boiler configuration was set at 72€ $t_{feedstock}^{-1}$ a^{-1} (22). In the case of the CHP configuration, as there is plenty of data on CHP systems (Table B-7), a whisker plot (Figure B-1) was used to determine the average value for AD systems with CHP units which resulted in 106.84 € $t_{feedstock}^{-1}$ a^{-1}. For the upgrading configuration, based on the systems installed the average value from the literature resulted in 158.67 € $t_{feedstock}^{-1}$ a^{-1} with a standard deviation of 29.46. Finally, for the upgrading + CHP configuration, a 15% additional cost was considered from the upgrading configuration which resulted in 182.47 € $t_{feedstock}^{-1}$ a^{-1}. For this configuration, the connection cost is not required so it was assumed the additional 15% came from the purchase of the CHP and boiler (if needed) units.

Table B-7 CAPEX cost of different AD systems in Ireland

Type of system	Feedstock (t a^{-1})	Capex (k€)	Capex (€ t^{-1} a^{-1})	Source
AD Plant	12,374	411.33	33.23	(23)
AD Plant	140,000	2,924	20.88	(24)
AD Plant + Boiler	2,500	188	72	(22)
AD Plant + CHP	25,550	1,628.57	63.7405	(25)
AD Plant + CHP	2,080	345.48	166.095	(26)
AD Plant + CHP	2,714	400.86	147.7	(26)
AD Plant + CHP	3,348	456.24	136.27	(26)
AD Plant + CHP	3,982	511.62	128.48	(26)
AD Plant + CHP	13,950	1,292.16	92.62	(27)
AD Plant + CHP	63,250	4,625.55	73.13	(27)
AD Plant + CHP	118,000	8,338.07	70.66	(27)
AD Plant + CHP	43,540	2,964.73	68.09	(28)
AD Plant + CHP	12,374	556.83	45.002	(23)
AD Plant + CHP	68,000	3,767	55.39	(22)
AD Plant + CHP	15,000	3,526	235	(22)
AD Plant + Upgrading	13,000	1,923	147.92	(22)
AD Plant + Upgrading	55,000	6,816	123.92	(22)
AD Plant + Upgrading	55,000	8,612	156.58	(22)
AD Plant + Upgrading	43,540	8,924.51	204.97	(28)
AD Plant + Upgrading	140,000	22,400	160	(24)

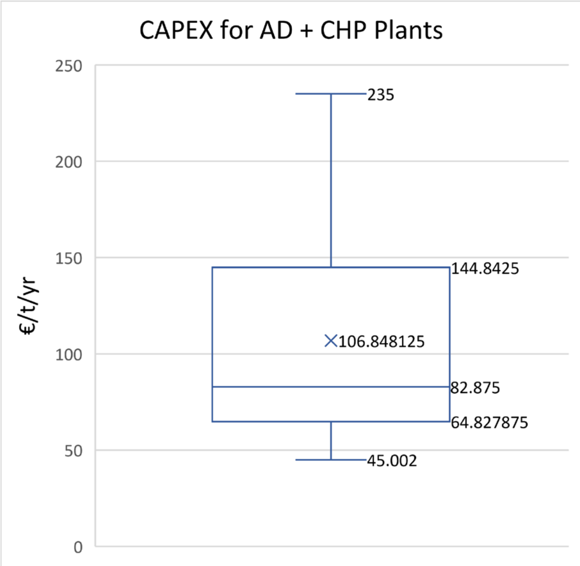

Figure B-1 Box and Whisker Plot of CAPEX for AD systems with CHP units.

Appendix B.8

The variable cost was calculated based on the total feedstock acquisition cost (TFC, € a^{-1}), the annual electricity expense of the system (CE, € a^{-1}), and the annual fuel expense (CH, € a^{-1}) based on the thermal and electrical demand of the system. The feedstock costs (TFC, € a^{-1}) were calculated based on the required feedstock resource and the individual feedstock cost (€ t_{wwt}^{-1}) of slurry and grass silage (see Equation B17). For the scenarios analysed, the slurry cost (FC_{CS}) is assumed to be 0 € t_{wwt}^{-1} as it is produced on the farm, while the grass silage price (FC_{GS}) was set at 43 € t_{wwt}^{-1} based on the average silage cost for 2022 in Ireland (29).

Equation B17 Total Feedstock Acquisition cost based on the feedstock resource (Grass Silage and Cattle Slurry) used for co-digestion in the AD plant.

$$TFC\left(\frac{€}{a}\right) = R_1^{CS} * FC_{CS} + R_2^{GS} * FC_{GS}$$

The annual electricity expense was calculated from two sources, the electricity demand of the AD process (ED_{AD}, kWh a^{-1}) and the biogas upgrading system (ED_{UP}, kWh a^{-1}). This expense only applied to scenarios with the boiler and upgrading configuration. To meet the electricity demand, electricity sourced from Ireland's electricity grid was considered with a commercial electricity price (PE) for 2022 based on the consumed amount which ranged between 237 €/MWh to 299 € MWh^{-1} (Table B-8) (30). The annual electricity expense for the AD process (CE_{AD}) was based on the electricity demand of the AD system (ED_{AD}, kWh a^{-1}) and the electricity price (PE) (Equation B18). In calculating the electricity expense of the upgrading system (CE_{UP}) the electricity demand of the upgrading process (ED_{UP}, kWh a^{-1}) will depend on the specific electricity demand (SE_{UP}, kWh m^{-3}biogas) of the biogas upgrading technology used and the quantity of biogas available for upgrading (V_{AD}, m^3 a^{-1}) (Equation B19).

Equation B18 Annual electricity expense calculation for the AD System.

$$CE_{AD}\left(\frac{€}{a}\right) = \frac{ED_{AD}}{1000} * PE$$

Equation B19 Annual electricity expense calculation for the Upgrading System.

$$CE_{UP}\left(\frac{€}{a}\right) = \frac{ED_{UP}}{1000} * PE$$

The annual fuel expense was sourced from both the thermal demand of the AD process (CH_{AD}) and the biogas upgrading system (CH_{UP}) selected. This expense only applied to the upgrading scenario (UPG). For both aspects, the cost was derived from the use of a specific fuel (natural gas, oil, and wood chips) combusted in a boiler to generate heat based on commercial prices (PF) for 2022. For natural gas, a price of 74.1 € MWh^{-1} was used based on the range of consumption of the systems while for the gas oil and fuel chips a delivered energy cost of 154.1 € MWh^{-1} and 460 € MWh^{-1} was used (Table B-8 and B-9) (30). The cost was then calculated based on the boiler efficiency (η_{Boiler}, $\eta_{Boiler-UPG}$) used to generate heat for the thermal demand of the AD process (TD_{AD}, MJ a^{-1}) and upgrading process (TD_{UP}, MJ a^{-1}) (if needed in Upgrading + CHP) and then multiplied by the price of fuel (Equation B20 and Equation B21).

Equation B20 Annual fuel expense calculation for the AD system.

$$CH_{AD}\left(\frac{€}{a}\right) = \left(\frac{TD_{AD}}{\eta_{Boiler/100}}\right)/3600 * PF$$

Equation B21 Annual fuel expense calculation for the Upgrading System.

$$CH_{UP}\left(\frac{€}{a}\right) = \left(\frac{TD_{UP}}{\eta_{Boiler-UPG/100}}\right)/3600 * PF$$

Table B-8 Commercial electricity cost in Ireland for July 2022 based on a biannual payment. Adapted from SEAI Commercial Fuel Cost Comparison (30).

Consumption Band	Range of Consumption (MWh a^{-1})	Average Price (€ MWh^{-1})
IA	<20	299
IB	>=20 <500	237.4
IC	>=500 <2,000	212.2
ID	>=2,000 <20,000	185.5
IE	>=20,000 <70,000	159.6
IF	>=70,000 <150,000	185.9

Table B-9 Commercial cost for natural gas in Ireland for July 2022 based on a biannual payment. Adapted from SEAI Commercial Fuel Cost Comparison (30).

Consumption Band	Range of Consumption (MWh a^{-1})	Average Price (€ MWh^{-1})
I1	<278	74.1
I2	>=278 <2,778	74.8
I3	>=2,778 <27,778	61.3
I4	>=27,778 <277,778	49.3

Table B-10 Commercial fuel cost in Ireland for July 2022. Adapted from SEAI Commercial Fuel Cost Comparison (30).

Fuel Type	Unit of Supply	Delivered Energy Cost (€ MWh^{-1})
Gas Oil 10ppm	Litre	154.1
Fuel Chips (35% moisture)	Kg wet	460

Appendix B.9

To calculate the amount of displaced synthetic fertiliser based on the use of digestate as organic fertiliser it was assumed that initially to grow grass for its use as silage synthetic fertilizer was spread at an amount of 185 kgN ha^{-1} to cover the total nitrogen requirement of the field (31). Additional to this, slurry was spread as organic fertiliser to enrich the content of potassium and phosphorous. To calculate the amount of nitrogen in the slurry (N_{Slurry}, kgN a^{-1}) the nitrogen content was based in the total solids (Table B-2) assuming a 50% N availability (32).

To calculate the annual change in nitrogen by using digestate as organic fertiliser (ΔF_{Sn}, kgN a^{-1}), the nitrogen contained in the digestate ($N_{Digestate}$) was subtracted from both the nitrogen of the slurry spread (N_{Slurry}, kgN/a) and the synthetic fertiliser used ($N_{Synthetic}$, kgN a^{-1}) as shown in Equation B22. In the case of the digestate, the amount of nitrogen contained in both the slurry and the grass silage was based on the amount of nitrogen contained in each feedstock total solids (Table B-2, Table B-3) assuming a 60% N availability (12).

Equation B22 Change in synthetic fertiliser based on digestate spread on the farm.

$$\Delta F_{SN}\left(\frac{kgN}{a}\right) = N_{Slurry} + N_{Synthetic} - N_{Digestate}$$

Box B1 Calculation of the amount of synthetic fertiliser displaced:

Scenario- 185 herd size.

<u>Amount of synthetic fertilizer with slurry.</u>

The amount of synthetic fertiliser was based on a requirement of 185 kgN ha^{-1}, considering a herd size of 185 cows on 46.4 ha of land; this translates to 8,584 kgN a^{-1}.

Based on the annual production of the 185-cow herd the total wet weight of the slurry amounts to 1,098.9 tFW a^{-1} (as per Equation B1 on Appendix B1). Assuming the total solids of the slurry accounts for 6.5% (Table B-2) of the wet weight that translates to 71.43 t a^{-1}, converting to kg the total will be 71,430 kg a^{-1}.

Assuming the nitrogen content in the total solids is 2% (Table B-2) the nitrogen content in the slurry will be 1,429 kgN a^{-1}, and considering that slurry has a has a

50% N availability the total available nitrogen will be 715 kgN a^{-1} (N_{Slurry}). This results in a total of 9,299 kgN a^{-1} spread on the land.

Amount of synthetic fertilizer with digestate.

To calculate the amount of nitrogen contained in the digestate the nitrogen contained in both feedstocks (cattle slurry and grass silage) was calculated. From the previous calculation the nitrogen found in the slurry accounts for 1,429 kgN a^{-1}.

For the first cut of grass, the total fresh weight amounts to 1,109.7 tFW a^{-1} (as per Equation B2 on Appendix B2). Assuming a total solids content of 29.27% (Table B-3), this equates to 324.8 t a^{-1}, or 324,800 kg a^{-1}. Assuming the nitrogen content in the total solids is 1.7% (Table B-3) the nitrogen content will be 5,421 kgN a^{-1}.

For the second cut of grass, the total fresh weight amounts to 1039.8 tFW a^{-1} (as per Equation B2 of Appendix B2). Assuming a total solids content of 17.85% (Table B-3), this equates to 185.6 t a^{-1}, or 185,600 kg a^{-1}. Assuming the nitrogen content in the total solids is 1% (Table B-3) the nitrogen content will be 1,856 kgN a^{-1}.

Adding the three sources of nitrogen above, the digestate has a total nitrogen content of 8,706 kgN a^{-1}. Assuming the digestate has a 60% N availability, the total available nitrogen will be 5,224 kgN a^{-1} ($N_{Digestate}$).

Inputting the three values into equation B22:

$$\Delta F_{SN}\left(\frac{kgN}{a}\right) = N_{Slurry} + N_{Synthetic} - N_{Digestate}$$
$$\Delta F_{SN}\left(\frac{kgN}{a}\right) = 715 + 8{,}584 - 5{,}224$$
$$\Delta F_{SN}\left(\frac{kgN}{a}\right) = 4{,}075$$

The amount of synthetic fertilizer required to meet the nitrogen demand of the field will be 4,075 kgN a^{-1} (88 kgN ha^{-1}). Accounting for the nitrogen of the digestate, this results in a nitrogen demand of 9,299 kgN a^{-1} to meet the requirements of the field.

Thus, a total of 4,509 kgN a^{-1} (8,584 kgN a^{-1} – 4,075 kgN a^{-1}) of synthetic fertiliser will be displaced which represents a reduction of 97 kgN per hectare.

Appendix B.10

For the emissions generated through the cultivation ($e_{ec,n}$) and savings from improved agricultural management ($e_{sca,n}$) from grass silage the calculations of Long et al. (33) were used. This includes the calculations for the emissions generated from the direct and indirect application of fertilisers and pesticides and the carbon sequestration savings. To calculate the total emissions generated by the direct application of each agro-chemical (synthetic fertiliser, pesticides, and herbicides) the amount used of each different chemical was multiplied by its respective emissions factors (Table B-11) and by the number of hectares used to grow the grass silage in the farm. Regarding the amount of nitrogen fertiliser used, the amount of synthetic fertilizer required per hectare (F_{SN}) was based on the change in synthetic fertilizer (ΔF_{SN}) from the use of the digestate as biofertiliser.

Table B-11 Emissions Factors from fertiliser and pesticides used during the cultivation of Grass Silage. Adapted from Long et al. (33).

Fertiliser and Pesticides for Grass Cultivation	Fertiliser Required (kg ha^{-1} a^{-1})	Emissions Factor (gCO_{2eq} ha^{-1} a^{-1})
N	F_{SN}	5917.2
P_2O_5	89.1	1013.5
K_20	370.5	579.3
CaO	1500	130
Pesticides / Herbicides	0.72	11025.7

As part of the emissions generated during cultivation ($e_{ec,n}$), the direct and indirect N_2O emissions generated from the application of the nitrogen synthetic fertiliser and the organic fertiliser were also calculated. This includes the direct N_2O emissions from managed soils, the Indirect N_2O emissions from atmospheric deposition, and the indirect N_2O emissions from leaching/runoff which were calculated with the following equations based on the Tier 1 IPCC methodology for managed soils (34).

Equation B23 Direct N_2O-N emissions from managed soils.

$$N_2O_{Direct} - N = (F_{SN} * EF_{1(Syn)}) + (F_O * EF_{1(Org)})$$

Equation B24 Indirect N_2O-N emissions from atmospheric deposition of N volatilised from managed soils.

$$N_2O_{(ATD)} - N = [(F_{SN} * Frac_{GASF}) + (F_O * Frac_{GASM})] * EF_4$$

Equation B25 Indirect N_2-O-N emissions from N leaching/runoff from managed soils.

$$N_2O_{(L)} - N = (F_{SN} + F_O) * Frac_{LEACH} * EF_5$$

Where, F_{SN} is the annual amount of synthetic fertiliser per hectare (kg ha^{-1} a^{-1} - after displacement), F_O is the amount of organic fertiliser spread per hectare (kg ha^{-1} a^{-1} - digestate), EF_1 is the emissions factor for N_2O emissions from N inputs (kgN_2O-N kgN^{-1} input), EF_4 is the emissions factor for N_2O emissions from atmospheric deposition of N on soils (kgN_2O-N kgN^{-1} input) and EF_5 is the emission factor for N_2O emissions from leaching and runoff (kgN_2O-N kgN^{-1} input). In Equation B24, $Frac_{GASF}$ represents the fraction of synthetic fertiliser that volatilises and $Frac_{GASM}$ represents the fraction of organic fertiliser that is deposited in the soil. In Equation B25, $Frac_{LEACH}$ represents the fraction of both organic and synthetic fertiliser of all N mineralised through leaching or runoff. To obtain the carbon intensity of the N_2O emissions ($CO_{2\text{-eq}}$) the N_2O-N emissions were converted to N_2O emissions by multiplying by the conversion factor (44/28) and by the global warming potential (GWP) for N_2O (298 $CO_{2\text{-eq}}$) (33). The emissions factors and fractions used were based on Ireland from the National Inventory Report as shown in Table B-12 (35).

Table B-12 Information related to Direct and Indirect N_20 emissions from managed soils. Adapted from the National Inventory Report for Ireland 2021 (35).

Parameter	Emissions Factor	Unit
$\boldsymbol{EF_{1(Syn)}}$	0.0124	Kg N_20-N Kg N^{-1}
$\boldsymbol{EF_{1(Org)}}$	0.006	Kg N_20-N Kg N^{-1}
$\boldsymbol{EF_4}$	0.01	Kg N_20-N Kg N^{-1}
$\boldsymbol{EF_5}$	0.011	Kg N_20-N Kg N^{-1}
$\boldsymbol{Frac_{GASF}}$	0.025	kg N volatilised per kg of N applied (synthetic fertilizer)
$\boldsymbol{Frac_{GASM}}$	0.085	kg N volatilised per kg of N applied (organic fertilizer)
$\boldsymbol{Frac_{LEACH}}$	0.1	kg N per kg of N additions

Box B2 Calculation of the emissions savings from the displacement of synthetic fertiliser:

Scenario- 185 herd size.

<u>Direct emissions from fertiliser use.</u>

To calculate the total emissions generated by the direct application of synthetic fertiliser before and after the use of digestate, the amount used of each different chemical was multiplied by its respective emissions factors (Table B-11), multiplied by the area of land considering a herd size of 185 cows on 46.4 ha of land, and then converted from $gCO_{2eq}\ a^{-1}$ to $kgCO_{2eq}\ a^{-1}$.

Direct Emissions with slurry as organic fertiliser

Fertiliser and Pesticides for Grass Cultivation	Fertiliser Required ($kg\ ha^{-1}\ a^{-1}$)	Emissions Factor ($gCO_{2eq}\ kg^{-1}$ Fertilizer)	Yearly Emissions ($kg\ CO_{2eq}\ a^{-1}$)
N	185	5,917.2	50,793.5
P_2O_5	89.1	1,013.5	4,191.3
K_20	370.5	579.3	9,958
CaO	1,500	130	9,045.7
Pesticides / Herbicides	0.72	11,025.7	368.4
Total Yearly Emissions ($kg\ CO_{2eq}\ a^{-1}$)			74,356.9

Direct Emissions with digestate as organic fertiliser

Fertiliser and Pesticides for Grass Cultivation	Fertiliser Required ($kg\ ha^{-1}\ a^{-1}$)	Emissions Factor ($gCO_{2eq}\ kg^{-1}$ Fertilizer)	Yearly Emissions ($kg\ CO_{2eq}\ a^{-1}$)
N	88	5,917.2	24,161.2
P_2O_5	89.1	1,013.5	4,191.3
K_20	370.5	579.3	9,958
CaO	1500	130	9,045.7
Pesticides / Herbicides	0.72	11,025.7	368.4
Total Yearly Emissions ($kg\ CO_{2eq}\ a^{-1}$)			47,724.6

The initial emissions with slurry as organic fertiliser were 74,356.9 $kgCO_{2eq}\ a^{-1}$, and reduced to 47,724.6 $kgCO_{2eq}\ a^{-1}$ by using digestate as organic fertiliser. This change results in a total savings of 26,632.3 $kgCO_{2eq}\ a^{-1}$ from the direct application of less synthetic fertiliser.

Direct and indirect N_2O emissions from fertiliser use.

Direct and Indirect N_2O Emissions with slurry as organic fertiliser

To obtain the direct and indirect emission N_2O emissions generated from the application of the nitrogen synthetic fertiliser and the slurry (organic fertiliser) we substitute the values in equation B23, B24 and B25 to obtain the N_2O-N emitted by each fertiliser. The emissions factors and fractions used were based on the National Inventory Report for Ireland 2021 (Table B-12).

$$N_2O_{Direct} - N = (F_{SN} * EF_{1(Syn)}) + (F_O * EF_{1(Org)})$$
$$N_2O_{Direct} - N = (185 * 0.0124) + (15.4 * 0.006)$$
$$N_2O_{Direct} - N = 2.39$$

$$N_2O_{(ATD)} - N = [(F_{SN} * Frac_{GASF}) + (F_O * Frac_{GASM})] * EF_4$$
$$N_2O_{(ATD)} - N = [(185 * 0.025) + (15.4 * 0.085)] * 0.01$$

$$N_2O_{(ATD)} - N = 0.06$$

$$N_2O_{(L)} - N = (F_{SN} + F_O) * Frac_{LEACH} * EF_5$$
$$N_2O_{(L)} - N = (185 + 15.4) * 0.1 * 0.011$$
$$N_2O_{(L)} - N = 0.22$$

The total N_2O-N emissions from synthetic fertiliser and slurry (organic fertiliser) accounts to a total of 2.67 kg N_2O-N /ha/yr. The emissions were then converted from N_2O-N emissions to N_2O emissions multiplying by a conversion factor (44/28) which results in 4.19 kg N_2O ha^{-1} a^{-1}. Considering that the global warming potential of N_2O is 298 and the area of land (46.4 ha) based on a herd size of 185 cows the total emissions account for 58,015 $kgCO_{2eq}$ a^{-1} emitted.

Direct and Indirect N_2O Emissions with digestate as organic fertiliser

To obtain the direct and indirect emission N_2O emissions generated from the application of the nitrogen synthetic fertiliser and the digestate (organic fertiliser) we substitute the values in equation B23, B24 and B25 to obtain the N_2O-N emitted by each fertiliser. The emissions factors and fractions used were based on the National Inventory Report for Ireland 2021 (Table B-12).

$$N_2O_{Direct} - N = (F_{SN} * EF_{1(Syn)}) + (F_O * EF_{1(Org)})$$
$$N_2O_{Direct} - N = (88 * 0.0124) + (112.6 * 0.006)$$
$$N_2O_{Direct} - N = 1.77$$

$$N_2O_{(ATD)} - N = [(F_{SN} * Frac_{GASF}) + (F_O * Frac_{GASM})] * EF_4$$
$$N_2O_{(ATD)} - N = [(88 * 0.025) + (112.6 * 0.085)] * 0.01$$
$$N_2O_{(ATD)} - N = 0.12$$

$$N_2O_{(L)} - N = (F_{SN} + F_O) * Frac_{LEACH} * EF_5$$
$$N_2O_{(L)} - N = (88 + 112.6) * 0.1 * 0.011$$
$$N_2O_{(L)} - N = 0.22$$

The total N_2O-N emissions from synthetic fertiliser and slurry (organic fertiliser) accounts to a total of 2.11 kg N_2O-N ha^{-1} a^{-1}. The emissions were then converted from N_2O-N emissions to N_2O emissions multiplying by a conversion factor (44/28) which results in 3.32 kg N_2O ha^{-1} a^{-1}. Considering that the global warming potential of N_2O is 298 and the area of land (46.4 ha) based on a heard size of 185 cows the total emissions account for 45,847 $kgCO_{2eq}$ a^{-1} emitted.

Subtracting the emissions generated from spreading slurry with synthetic fertiliser (58,015 $kgCO_{2eq}$ a^{-1}) from the emissions generated spreading digestate with synthetic fertiliser (45,847 $kgCO_{2eq}$ a^{-1}), the change of organic fertiliser results in a total savings of 12,168 $kgCO_{2eq}$ a^{-1}. Adding the savings from direct application (26,632.3 $kgCO_{2eq}$ a^{-1}) and from direct and indirect N_2O emissions (12,168 $kgCO_{2eq}$ a^{-1}), a total emissions savings of 38,800 $kgCO_{2eq}$ a^{-1} is obtained from the displacement of synthetic fertiliser.

For the savings from agricultural management ($e_{sca,n}$) emissions savings were assumed to be 2.2 tCO_2 ha^{-1} a^{-1} based on the soil carbon sequestration from the grass silage (33). In the case of slurry, there are no emissions associated with cultivation ($e_{ec,n}$) so these were assumed to be zero. For the carbon sequestration savings ($e_{sca,n}$), based on the RED II methodology a bonus of -54 $kgCO_{2eq}$ t_{wwt}^{-1} was used as manure used in the AD process as a substrate is considered attributed to improvements in manure management which reduce associated fugitive methane e missions (36).

The emissions from the transport of feedstock for both slurry and grass silage ($e_{td,feedstock,n}$) were considered zero as it is assumed that both feedstocks were produced on the farm under analysis. The same applied to the emissions from carbon stock changes ($e_{l,n}$) as there is no land-use change considered for the farm under analysis. The emissions from production (e_p) were considered to come from methane leaks during the AD and upgrading processes, from fuel (natural gas, oil, and wood chips) used to cover the thermal demand of the processes and from the use of electricity from the electricity grid. To calculate the emissions from fuel and electricity use, emissions factors recommended for Ireland were used as shown in Table B-13. Finally, the emissions from methane leaks were obtained based on a GWP of 25 CO_{2-eq} (33). For the anaerobic digestion process a methane leak of 2% was considered while the methane leak from upgrading due methane slip (CH_4Slip_{UP}) a regenerative thermal oxidiser at the end of the upgrading process was considered to reduce the methane concentration in the off-gas by 99. 5% (37).

Table B-13 Emissions factor for CO_2 per unit of energy for fuels. Values of electricity and natural gas change annually. Adapted from the SEIA Conversion Factors for energy use in Ireland (37).

Emissions Factor Energy	gCO_2 kWh^{-1}
Electricity 2020	295.8
Natural Gas 2021	202.2
Fuel Oil	273.6
Woodchips	0
Diesel	263.9

For the scenarios that considered the upgrading configurations it was assumed that the biomethane would be transported through the natural gas grid, so the emissions generated from transport and distribution ($e_{td,product}$) were considered to be 1.22 gCO_2eq per $MJ_{biomethane}$ based on previous studies (33). For the emissions from the fuel in use (e_u) these were set to be zero as the RED II methodology recommends that the emissions from the combustion of biomass fuels shall be taken as zero. The emissions savings from CO_2 capture and geological storage (e_{ccs}) and CO_2 capture and replacement of fossil fuels (e_{ccr}) were considered zero for this analysis.

To calculate the emissions saved from the displacement of synthetic fertilizer replaced by digestate (e_{fd}) the emission generated during cultivation and the direct and indirect emissions generated from the application of synthetic fertiliser (185 kgN ha^{-1}) and organic fertiliser (slurry) used originally in the farm were subtracted from the emissions generated from the amount of synthetic fertiliser displaced (ΔF_{SN}- kgN a^{-1}) from the use of digestate as organic fertiliser. The savings are then obtained subtracting the total emissions calculated previously for cultivation ($e_{ec,n}$) using digestate from the base case without organic fertiliser which considers the original amount of synthetic fertilizer (F_{SN}- 185 kg ha^{-1} a^{-1}) and slurry as the organic fertiliser (F_O).

The emissions saved from displacement of energy (e_{fd}) consider the electricity and heat displaced from the energy output of the configurations (HO_{CHP}, HO_{Boiler} and EO_{CHP}- kWh a^{-1}) and from the amount of fuel displaced (diesel) if biomethane is used as a transport fuel. For the emissions saved from fuel displaced, it was assumed that biomethane would be used in the form of compressed natural gas (CNG), based on this assumption the energy output of the biomethane (EO_{UP} -kWh a^{-1}) was multiplied by the average fuel consumption factor of CNG relative to diesel considered for this study to be 88% based on literature values (38), and multiplied by the emissions factor of diesel for Ireland (Table B-13). Finally, the emissions from energy displaced were obtained for heat by multiplying the heat output of the CHP and Boiler configuration (HO_{CHP}, HO_{Boiler}- kWh a^{-1}) by the emissions factor of natural gas while for electricity the electricity produced by the CHP configuration (EO_{CHP} -kWh a^{-1}) was multiplied by the emissions factor for electricity (Table B-13). The emissions savings from the displacement of heat and electricity are based on the current emissions generated from the production of natural gas (202 gCO_2 kWh^{-1}) and electricity (346 gCO_2 kWh^{-1}) for Ireland for 2021 (39).

Appendix B.11

Table B-14 Summary of the annual operative cost for each of the 16 scenarios assessed divided by the end-gas configuration and herd size.

Configuration	Herd Size	Labour	Maintenance	Insurance	Administrative Cost	Electricity Cost	Fuel Cost	Feedstock Cost	Total Annual Cost
Boiler	40	€5,160	€1,354	€677	€451	€1,874	€0	€16,732	€26,248
	60	€5,160	€2,301	€1,150	€767	€3,185	€0	€30,477	€43,040
	100	€5,160	€3,725	€1,862	€1,242	€5,156	€0	€48,603	€65,747
	185	€5,160	€7,016	€3,508	€2,339	€7,712	€0	€92,426	€118,161
CHP	40	€5,160	€2,009	€1,004	€670	€0	€0	€16,732	€25,575
	60	€5,160	€3,414	€1,707	€1,138	€0	€0	€30,477	€41,896
	100	€5,160	€5,527	€2,763	€1,842	€0	€0	€48,603	€63,896
	185	€5,160	€10,412	€5,206	€3,471	€0	€0	€92,426	€116,674
UPG	40	€15,480	€2,983	€1,492	€994	€8,724	€2,623	€16,732	€49,029
	60	€15,480	€5,070	€2,535	€1,690	€15,579	€4,233	€30,477	€75,065
	100	€15,480	€8,208	€4,104	€2,736	€24,949	€6,505	€48,603	€110,586
	185	€15,480	€15,462	€7,731	€5,154	€47,320	€11,576	€92,426	€195,150
UPG+CHP	40	€15,480	€3,431	€1,715	€1,144	€0	€0	€16,732	€38,502
	60	€15,480	€5,831	€2,915	€1,944	€0	€0	€30,477	€56,647
	100	€15,480	€9,439	€4,720	€3,146	€0	€0	€48,603	€81,388
	185	€15,480	€17,782	€8,891	€5,927	€0	€0	€92,426	€140,506

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Appendix B.12

Table B-16 Summary of the annual emissions savings, and emissions generated in kg CO_{2eq} for each of the 16 scenarios assessed divided by the end-gas configuration and herd size.

Configuration	Herd Size	Emissions Savings					Emissions Generated						
		Energy Replacement (Electricity and Heat)	**Fuel Replacement (Diesel)**	**Carbon Sequestration**	**Savings from fertiliser displacement**	**Slurry Management (-54 kg CO_{2eq} tFW^{-1})**	**Fertiliser Direct Emissions**	**N_2O emissions from fertiliser application**	**Biogas Production**	**Emissions from Upgrading**	**Emissions From Process Leakage**	**Grid Transport**	**Net GHG Emissions**
Boiler	40	-56877	0	-17383	-7230	-762	8000	7808	1854	0	14823	0	-49767
	60	-103726	0	-31997	-13084	-951	14782	14223	3151	0	26526	0	-91076
	100	-166429	0	-50914	-20895	-1653	23503	22682	5101	0	42462	0	-146143
	185	-317952	0	-96955	-39701	-2979	44779	43134	9609	0	80558	0	-279508
CHP	40	-60924	0	-17383	-7230	-762	8000	7808	0	0	12970	0	-57521
	60	-111210	0	-31997	-13084	-951	14782	14223	0	0	23376	0	-104862
	100	-178327	0	-50914	-20895	-1653	23503	22682	0	0	37362	0	-168243
	185	-340623	0	-96955	-39701	-2979	44779	43134	0	0	70949	0	-321397
UPG	40	0	-75713	-17383	-7230	-762	8000	7808	8295	8836	30101	1436	-36611
	60	0	-136461	-31997	-13084	-951	14782	14223	13547	15936	52858	2589	-68558
	100	0	-218109	-50914	-20895	-1653	23503	22682	21076	25467	83904	4138	-110801
	185	0	-414185	-96955	-39701	-2979	44779	43134	38039	48365	157352	7858	-214293
UPG+CHP	40	0	-55333	-17383	-7230	-762	8000	7808	0	0	12919	1050	-50931
	60	0	-100078	-31997	-13084	-951	14782	14223	0	0	23285	1899	-91921
	100	0	-159838	-50914	-20895	-1653	23503	22682	0	0	37217	3033	-146865
	185	0	-303671	-96955	-39701	-2979	44779	43134	0	0	70675	5761	-278957

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1. Hennessy T, Buckley C, Cushion M. teagasc. 2011 [cited 2022 Mar 10]. National farm survey of manure application and storage practices on Irish farms. Available from: https://www.teagasc.ie/media/website/publications/2011/TeagascNationalFarmSurveyOfManureApplication.pdf

2. Buckley C, Moran B, Donnellan T. Teagasc National Farm Survey A Report on Bovine Manure Management, Application and Storage Practices in Ireland Rural Economy and Development Programme.

3. Murphy JD, Power NM. An argument for using biomethane generated from grass as a biofuel in Ireland. Biomass Bioenergy. 2009 Mar 1;33(3):504–12.

4. Meehan P, Burke B, Doyle D, Barth S, Finnan J. Exploring the potential of grass feedstock from marginal land in Ireland: Does marginal mean lower yield? Biomass Bioenergy. 2017 Dec 1;107:361–9.

5. Smyth BM, Murphy JD, O’Brien CM. What is the energy balance of grass biomethane in Ireland and other temperate northern European climates? Renewable and Sustainable Energy Reviews. 2009 Dec 1;13(9):2349–60.

6. Holen NM, Brereton AJ. Vol. 41, Irish Journal of Agricultural and Food Research. 2022 [cited 2022 Jun 14]. p. 213–26 An Assessment of the Potential Impact of Climate Change on Grass Yield in Ireland over the Next 100 Years on JSTOR. Available from: https://www.jstor.org/stable/25562465?seq=1

7. KPMG, Devenish, Gas Networks Ireland. Sustainability of Biomethane Production in Ireland Exploring how Ireland can deliver a sustainable, agriculture-led biomethane industry [Internet]. 2021 [cited 2022 Jul 21]. Available from: https://www.gasnetworks.ie/biomethane-sustainability-report-2021.pdf

8. Teagasc. Fertilising 2 nd Cut Grass Silage [Internet]. [cited 2022 Aug 4]. Available from: https://www.teagasc.ie/media/website/crops/soil-and-soil-fertility/2nd-Cut-Grass-Silage-N,-P-K-Req.pdf

9. McEniry J, Crosson P, Finneran E. JSTOR. 2013 [cited 2022 Nov 16]. How much grassland biomass is available in Ireland in excess of livestock requirements? Available from: https://www.jstor.org/stable/23631018

10. Allen E, Wall DM, Herrmann C, Murphy JD. A detailed assessment of resource of biomethane from first, second and third generation substrates. Renew Energy. 2016 Mar 1;87:656–65.

11. O'Shea R, Wall DM, Kilgallon I, Browne JD, Murphy JD. Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region. Appl Energy. 2017 Feb 15;188:237–56.

12. O'Shea R, Lin R, Wall DM, Browne JD, Murphy JD. Using biogas to reduce natural gas consumption and greenhouse gas emissions at a large distillery. Appl Energy. 2020 Dec 1;279:115812.

13. ASHRAE. Handbook - Fundamentals (SI). Climatic design conditions for Cork 2009/2013/2017 [Internet]. 2017 [cited 2022 Jun 2]. Available from: http://ashrae-meteo.info/v2.0/?lat=51.841&lng=-8.491&place=%27%27&wmo=039550&si_ip=SI&ashrae_version=2017

14. IEA Bioenergy Task 37. Pioneering biogas farming in Central Finland. Farm scale biogas plant produces vehicle fuel, heat, electricity and bio-fertilizer [Internet]. 2012 [cited 2022 Jun 16]. Available from: https://www.ieabioenergy.com/blog/publications/pioneering-biogas-farming-in-central-finland/

15. Bauer F, Hulteberg C, Persson T, Tamm D. Biogas upgrading-Review of commercial technologies; Biogasuppgradering-Granskning av kommersiella tekniker. 2013 [cited 2022 Jun 15]; Available from: https://www.osti.gov/etdeweb/biblio/22090519

16. Sun Q, Li H, Yan J, Liu L, Yu Z, Yu X. Selection of appropriate biogas upgrading technology-a review of biogas cleaning, upgrading and utilisation. Renewable and Sustainable Energy Reviews. 2015 Nov 1;51:521–32.

17. Mamone RM. Small-Scale Biogas Upgrading with Membranes: A Farm Based Techno-Economic and Social Assessment for Sustainable Development. 2014 [cited 2022 Jun 16]; Available from: https://www.diva-portal.org/smash/record.jsf?pid=diva2:745594

18. Wu B, Lin R, O'Shea R, Deng C, Rajendran K, Murphy JD. Production of advanced fuels through integration of biological, thermo-chemical and power to gas

technologies in a circular cascading bio-based system. Renewable and Sustainable Energy Reviews. 2021 Jan 1;135:110371.

19. O'Shea R, Wall DM, Kilgallon I, Browne JD, Murphy JD. Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region. Appl Energy. 2017 Feb 15;188:237–56.

20. Nolan T, Troy SM, Gilkinson S, Frost P, Xie S, Zhan X, et al. Economic analyses of pig manure treatment options in Ireland. Bioresour Technol. 2012 Feb 1;105:15–23.

21. Forbes EGA, Olave RJ, Johnston CR, Browne JD, Relf J. Biomass and bio-energy utilisation in a farm-based combined heat and power facility. Biomass Bioenergy. 2016 Jun 1;89:172–83.

22. Ricardo Energy & Environment. Assessment of Cost and Benefits of Biogas and Biomethane in Ireland [Internet]. 2017 [cited 2022 Aug 4]. Available from: https://www.seai.ie/publications/Assessment-of-Cost-and-Benefits-of-Biogas-and-Biomethane-in-Ireland.pdf

23. Nolan T, Troy SM, Gilkinson S, Frost P, Xie S, Zhan X, et al. Economic analyses of pig manure treatment options in Ireland. Bioresour Technol. 2012 Feb 1;105:15–23.

24. Rajendran K, Browne JD, Murphy JD. What is the level of incentivisation required for biomethane upgrading technologies with carbon capture and reuse? Renew Energy. 2019 Apr 1;133:951–63.

25. Biogas Go Global. Kroghsminde Biogas Plant [Internet]. [cited 2022 Aug 4]. Available from: https://www.biogasgoglobal.com/cases/combigas

26. O'Connor S, Ehimen E, Pillai SC, Lyons G, Bartlett J. Economic and Environmental Analysis of Small-Scale Anaerobic Digestion Plants on Irish Dairy Farms. Energies 2020, Vol 13, Page 637 [Internet]. 2020 Feb 3 [cited 2022 May 23];13(3):637. Available from: https://www.mdpi.com/1996-1073/13/3/637/htm

27. Dennehy C, Lawlor PG, Gardiner GE, Jiang Y, Shalloo L, Zhan X. Stochastic modelling of the economic viability of on-farm co-digestion of pig manure and food waste in Ireland. Appl Energy. 2017 Nov 1;205:1528–37.

28. Goulding D, Power N. Which is the preferable biogas utilisation technology for anaerobic digestion of agricultural crops in Ireland: Biogas to CHP or biomethane as a transport fuel? Renew Energy. 2013 May 1;53:121–31.

29. The cost of producing home-grown feeds - Teagasc | Agriculture and Food Development Authority [Internet]. [cited 2022 Sep 20]. Available from: https://www.teagasc.ie/animals/beef/grange/beef2022-open-day/the-cost-of-producing-home-grown-feeds--/

30. SEAI. Commercial / Industrial Fuels 01-Jul-22 Comparison of Energy Costs [Internet]. 2022 [cited 2022 Sep 20]. Available from: www.seai.ie/data-and-insights/seai-statistics/key-publications/

31. Teagasc. Grassland - Grass Silage and Hay [Internet]. 2022 [cited 2022 Sep 20]. Available from: https://www.teagasc.ie/crops/soil--soil-fertility/grassland/grass-silage-and-hay/

32. Crops - Make full use of Cattle Slurry - Teagasc | Agriculture and Food Development Authority [Internet]. [cited 2023 May 5]. Available from: https://www.teagasc.ie/news--events/daily/crops/make-full-use-of-cattle-slurry.php

33. Long A, Murphy JD. 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. 2019 Nov 1;115:109347.

34. Walsh M, Williams SA. Agriculture, Forestry and Other Land Use 11. 2006;4.

35. Duffy P, Black K, Fahey D. Ireland National Inventory Report 2021 [Internet]. 2021 Apr [cited 2022 Jun 29]. Available from: https://unfccc.int/documents/271533

36. European Commission. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) [Internet]. 2018 [cited 2022 Jul 21]. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC

37. Kvist T, Aryal N. Methane loss from commercially operating biogas upgrading plants. Waste Management. 2019 Mar 15;87:295–300.

38. Speirs J, Balcombe P, Blomerus P, Stettler M, Achurra-Gonzalez P, Woo M, et al. Natural gas fuel and greenhouse gas emissions in trucks and ships. Progress in Energy [Internet]. 2020 Jan 20 [cited 2022 Sep 23];2(1):012002. Available from: https://iopscience-iop-org.ucc.idm.oclc.org/article/10.1088/2516-1083/ab56af

39. Conversion Factors | SEAI Statistics | SEAI [Internet]. [cited 2022 Aug 12]. Available from: https://www.seai.ie/data-and-insights/seai-statistics/conversion-factors/

Appendix C

Appendix C.1

Table C-26 Results from the anaerobic digestion process for the base case scenario of the 4 different farm scales.

Anaerobic Digestion Results				
Farm Size	40	60	100	185
Slurry Feedstock (t_{wwt} a^{-1})	238	356	594	1,099
Grass Silage Feedstock First Cut (t_{wwt} a^{-1})	201	366	584	1,110
Grass Silage Feedstock Second Cut (t_{wwt} a^{-1})	188	343	547	1,040
Total Mass of Fedstock (t_{wwt} a^{-1})	627	1,065	1,724	3,248
Digestate Mass (t a^{-1})	539	906	1,470	2,766
N content of Digestate (kg a^{-1})	1651	2908	4671	8843
Biogas Production (m^3 a^{-1})	66,381	119,717	191,321	363,346
Gross Energy Ouput (MJ a^{-1})	1,252,600	2,257,613	3,608,398	6,852,268
Electric Demand (kWh a^{-1})	6,267	10,652	17,243	32,483
Thermal Demand (MJ a^{-1})	114,686	185,101	284,425	506,172

Appendix C.2

Table C.27 Main energy outputs and energy demands of the different configurations of the 16 base case scenarios.

Biogas end-use Configurations					
Configuration	Farm Size	40	60	100	185
Boiler (B)	**Net Heat Output (MWh a^{-1})**	281,293	512,986	823,093	1,572,464
	Boiler Size (kW_{th})	38	68	109	207
CHP	**Net Heat Output (kWh a^{-1})**	159,604	290,360	467,264	896,754
	Net Electrical output (kWh a^{-1})	100,983	177,483	283,457	538,539
	CHP size (kW_e)	13	23	36	69
Upgrading (U)	**Electric Demand (kWh a^{-1})**	29872	53873	86095	163506
	Biomethane Produced (m^3 a^{-1})	34002	61283	97950	186004
	Off gas Methane Content (kg a^{-1})	7.5	13.5	21.7	41.1
UPG+CHP (U+CHP)	**Biogas Input for the CHP unit (m^3 a^{-1})**	17,869	31,919	51,114	96,949
	Biogas for Upgrading (m^3 a^{-1})	48,513	87,798	140,207	266,397
	Biomethane Produced (m^3 a^{-1})	24,849	44,943	71,781	136,374
	CHP size (KW_e)	3.40	6.08	9.73	18.45
	CHP Electric Output (kWh a^{-1})	28,098	50,161	80,336	152,362
	CHP Heat Output (kWh a^{-1})	48,703	86,945	139,250	140,603
	Off gas Methane Content (kg a^{-1})	5.5	9.9	15.9	30.1

Appendix C.3

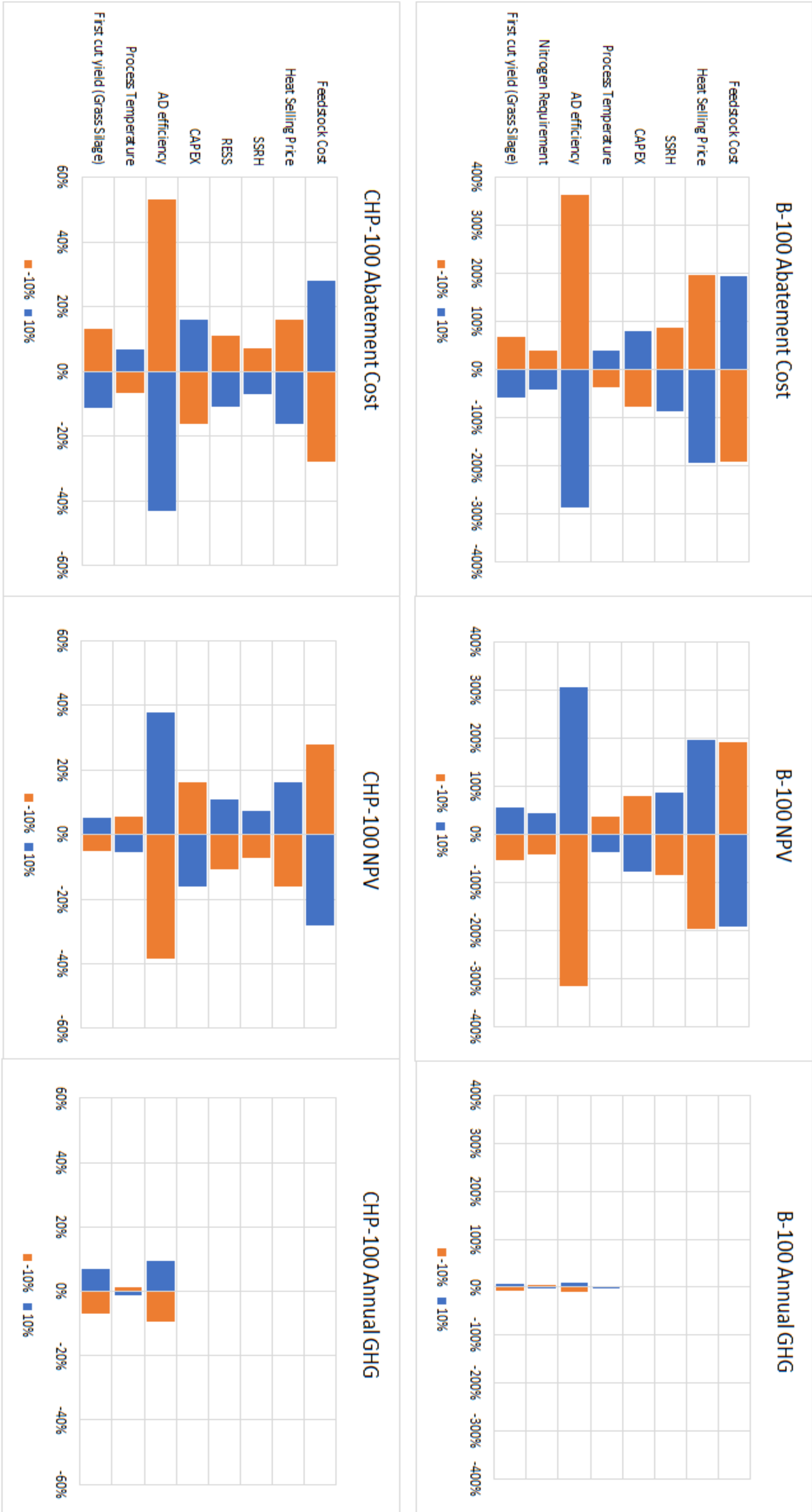

Figure C.9 Results of the sensitivity analysis of B and CHP configurations for on-farm anaerobic digestion based on a herd of 100 dairy cows. The results for each cell indicate a change in abatement cost, NPV and annual GHG emissions with a ± 10% alteration in the parameter considered (e.g. SSRH, CAPEX or feedstock cost)

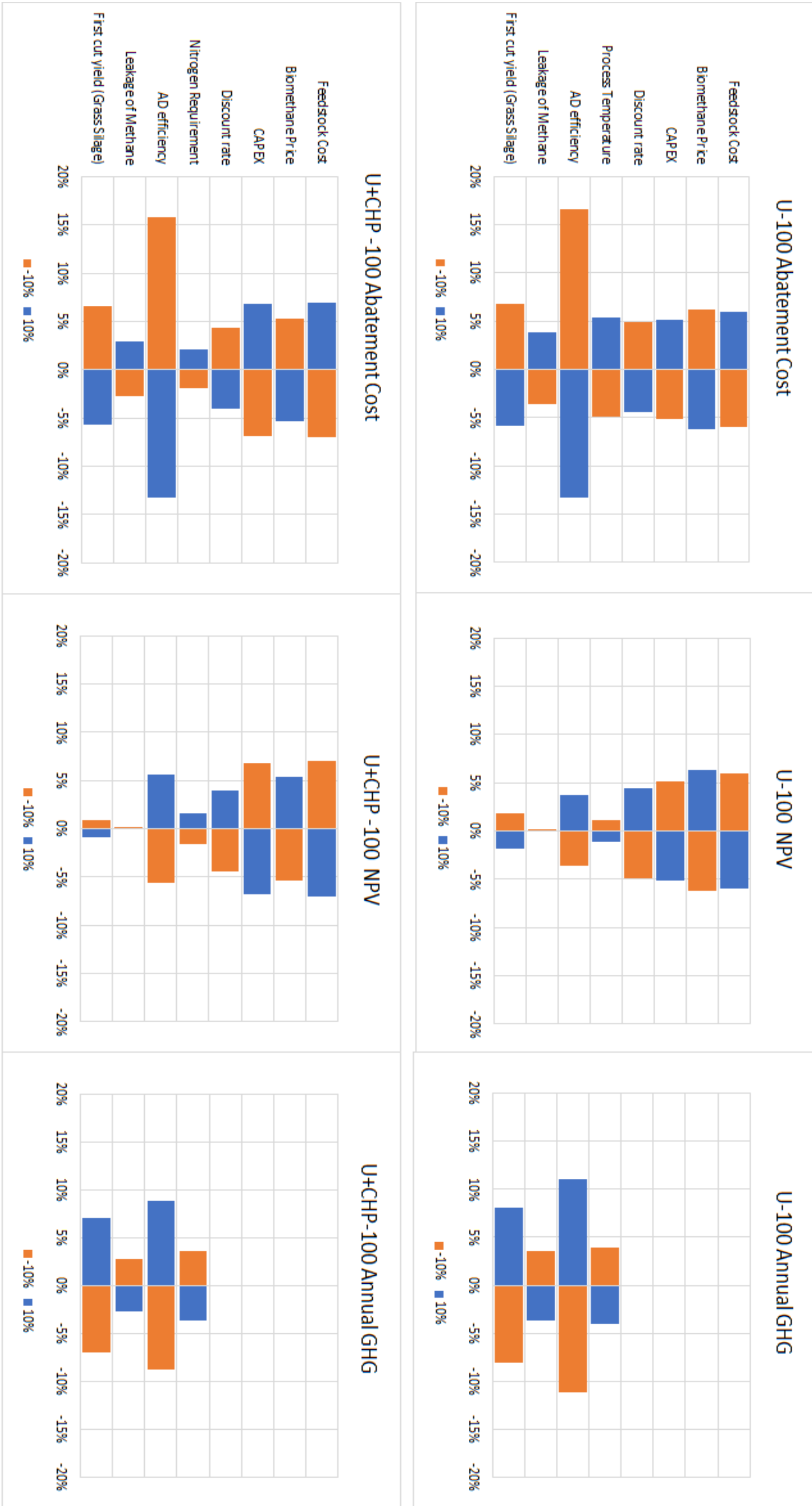

Figure C.10 Results of the sensitivity analysis of U and U+CHP configurations for on-farm anaerobic digestion based on a herd of 100 dairy cows. The results for each cell indicate a change in abatement cost, NPV and annual GHG emissions with a ± 10% alteration in the parameter considered (e.g. SSRH, CAPEX or feedstock cost)

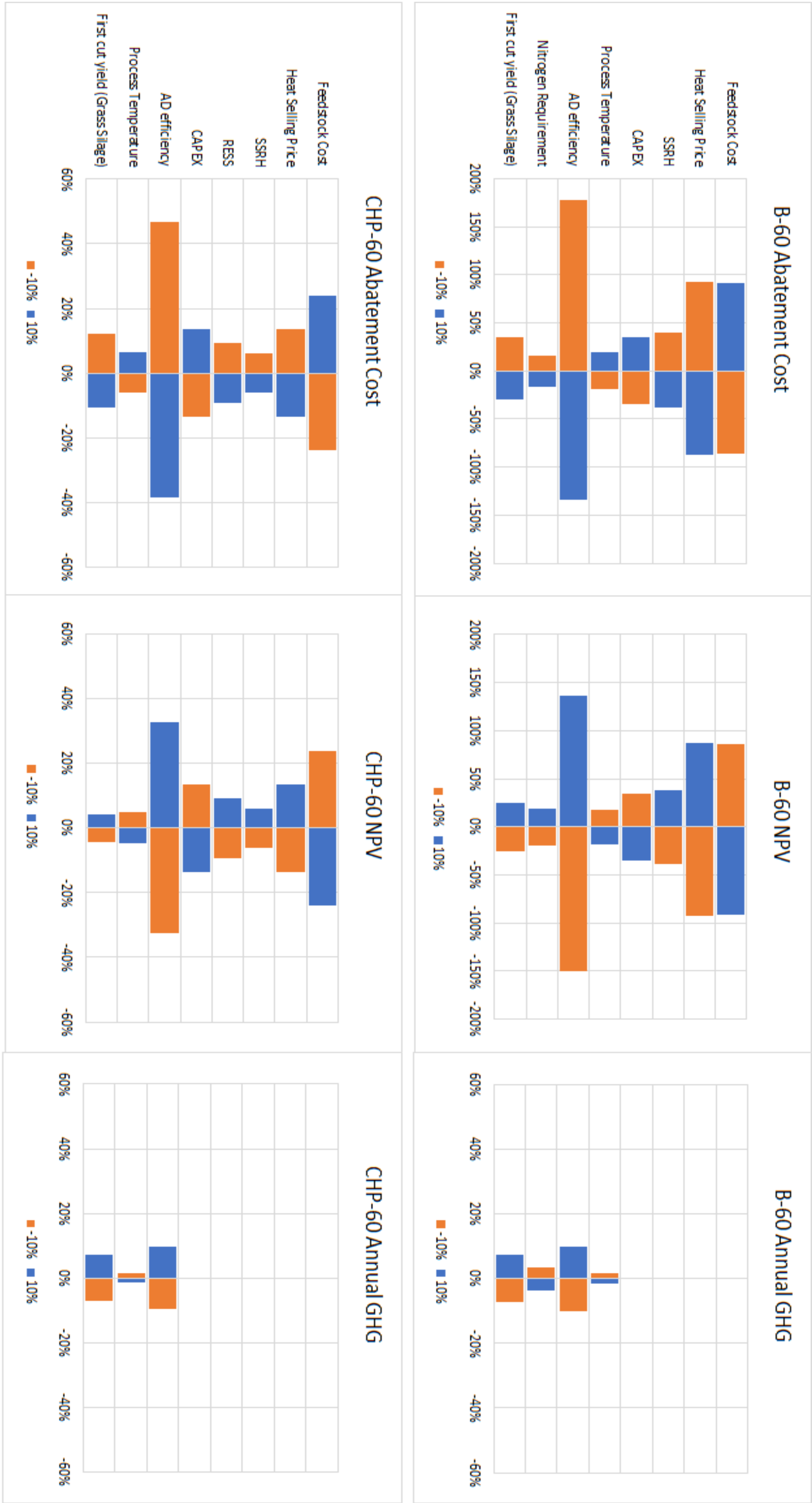

Figure C.11 Results of the sensitivity analysis of B and CHP configurations for on-farm anaerobic digestion based on a herd of 60 dairy cows. The results for each cell indicate a change in abatement cost, NPV and annual GHG emissions with a ± 10% alteration in the parameter considered (e.g. SSRH, CAPEX or feedstock cost)

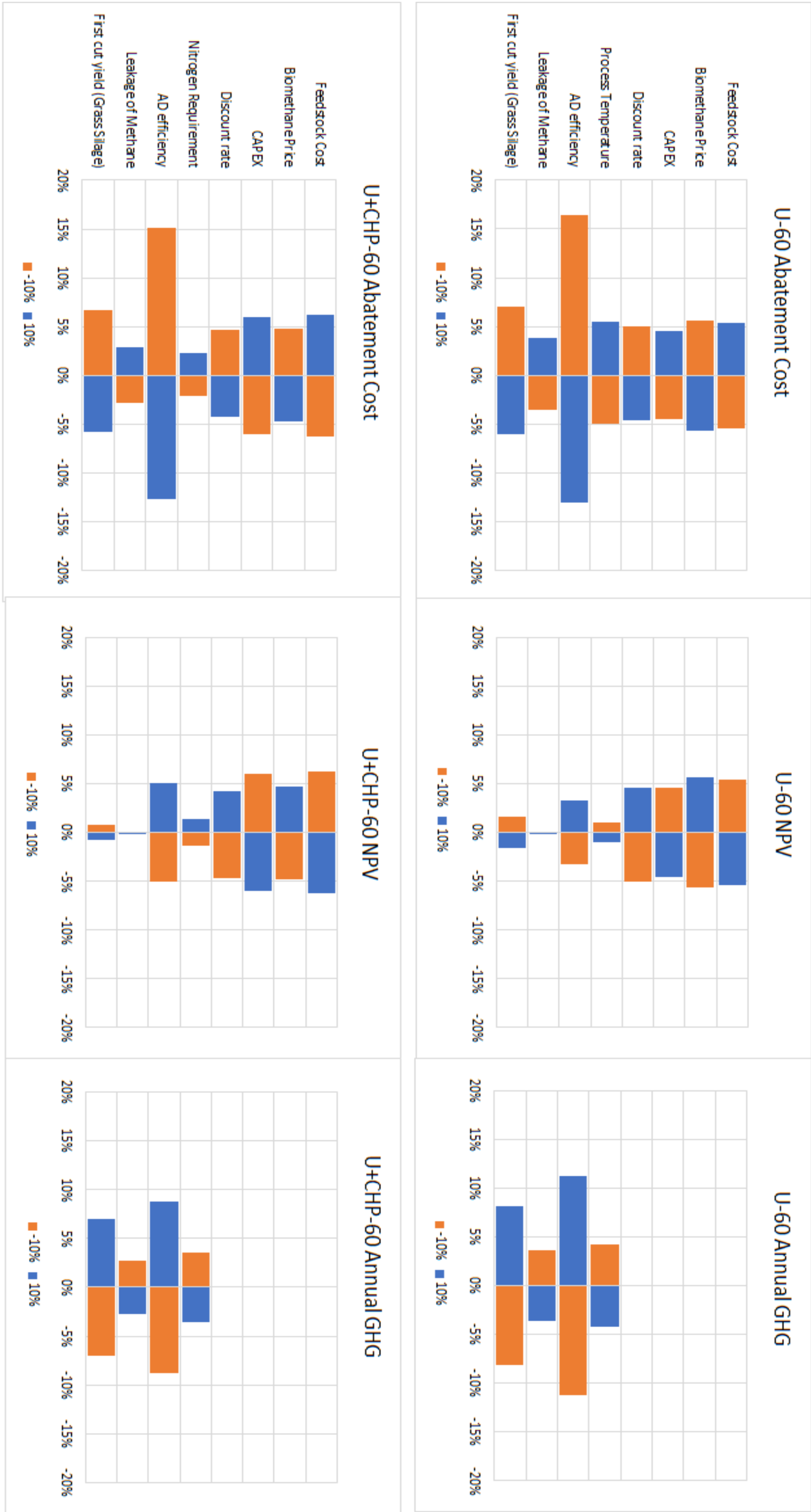

Figure C.12 Results of the sensitivity analysis of U and U+CHP configurations for on-farm anaerobic digestion based on a herd of 60 dairy cows. The results for each cell indicate a change in abatement cost, NPV and annual GHG emissions with a ± 10% alteration in the parameter considered (e.g. SSRH, CAPEX or feedstock cost)

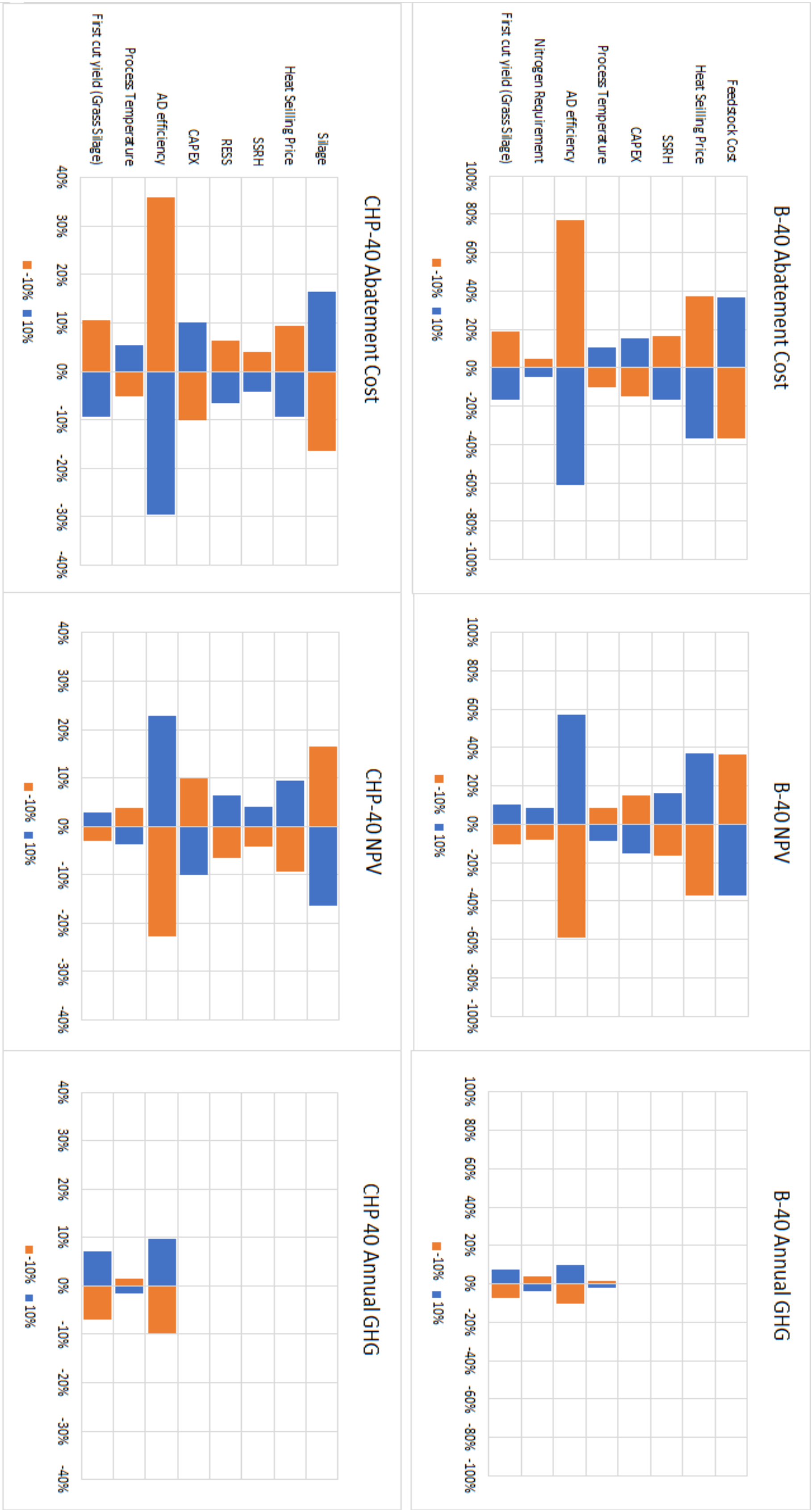

Figure C.13 Results of the sensitivity analysis of B and CHP configurations for on-farm anaerobic digestion based on a herd of 40 dairy cows. The results for each cell indicate a change in abatement cost, NPV and annual GHG emissions with a ± 10% alteration in the parameter considered (e.g. SSRH, CAPEX or feedstock cost)

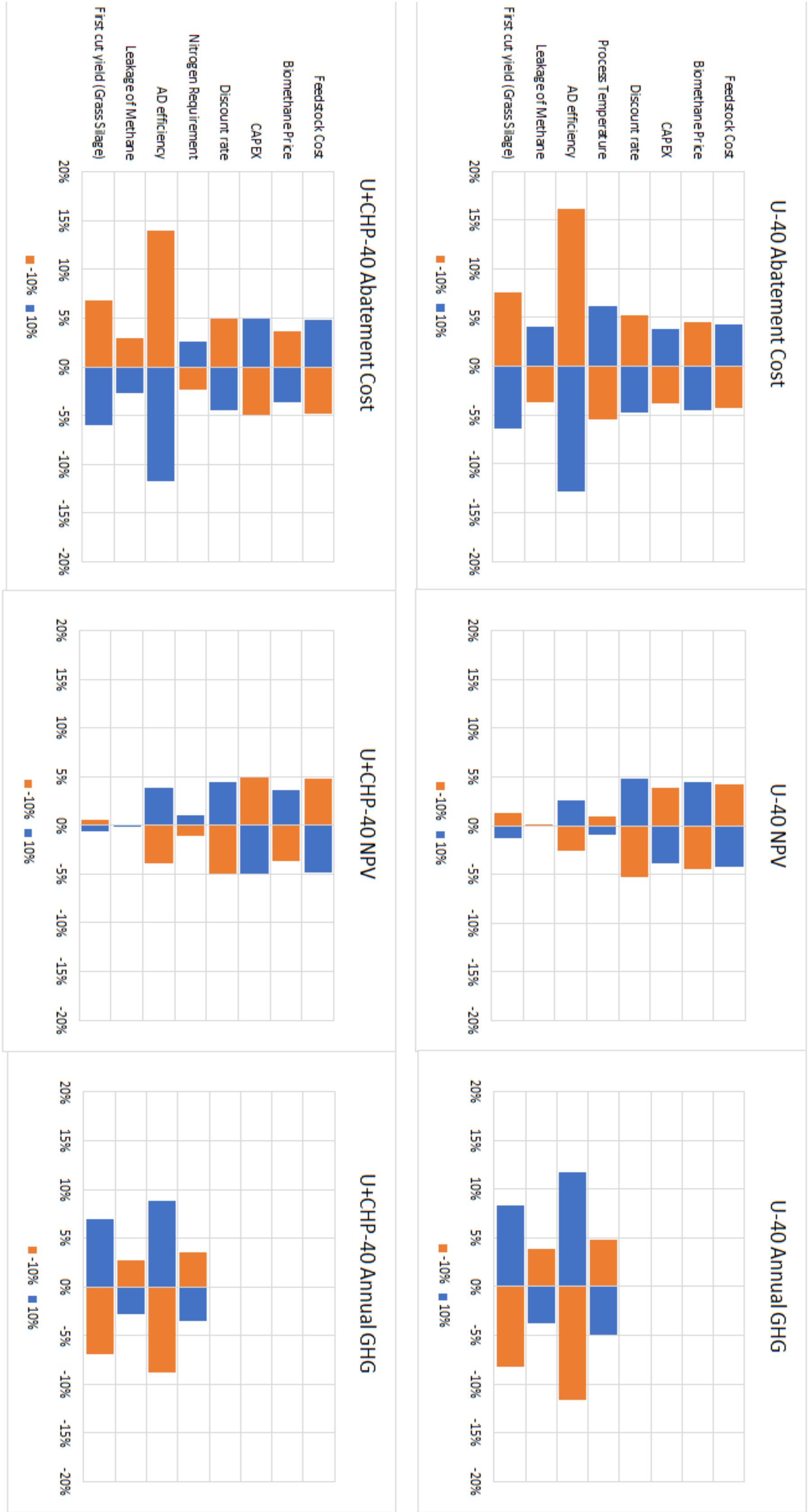

Figure C.14 Results of the sensitivity analysis of U and U+CHP configurations for on-farm anaerobic digestion based on a herd of 40 dairy cows. The results for each cell indicate a change in abatement cost, NPV and annual GHG emissions with a ± 10% alteration in the parameter considered (e.g. SSRH, CAPEX or feedstock cost)

Appendix C.4

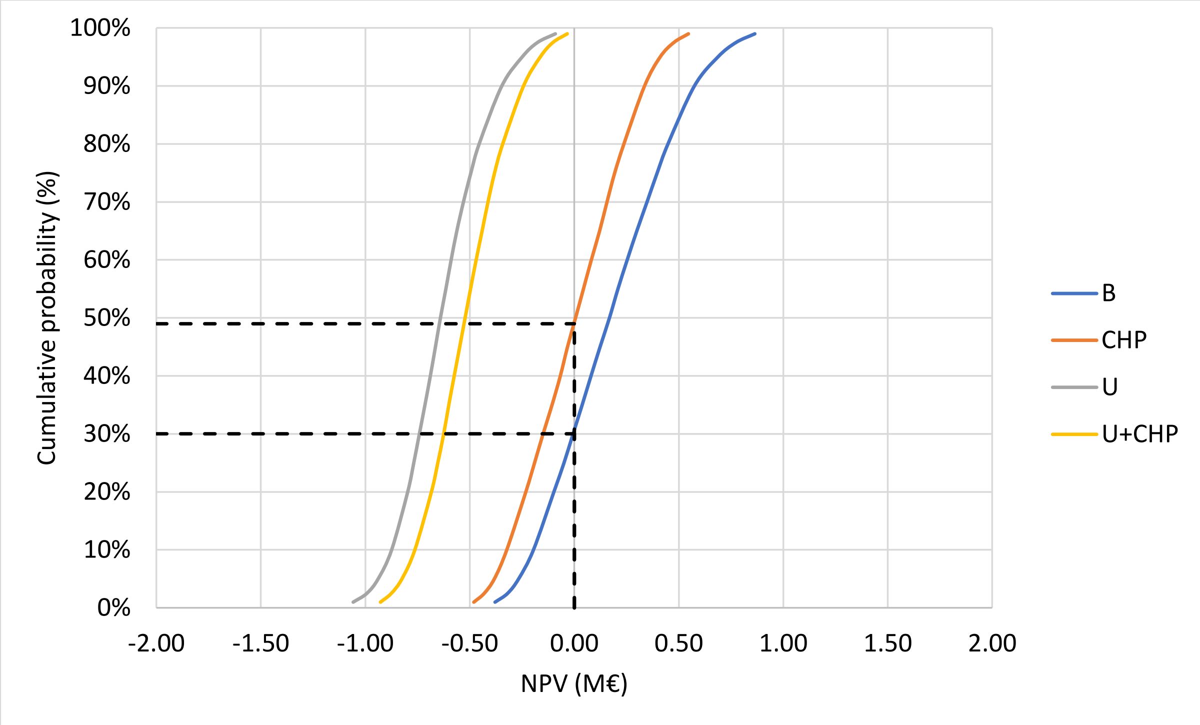

Figure C.15 Cumulative distribution function of the Net Present Value for the 4 biogas-end use configurations for a herd size of 100.

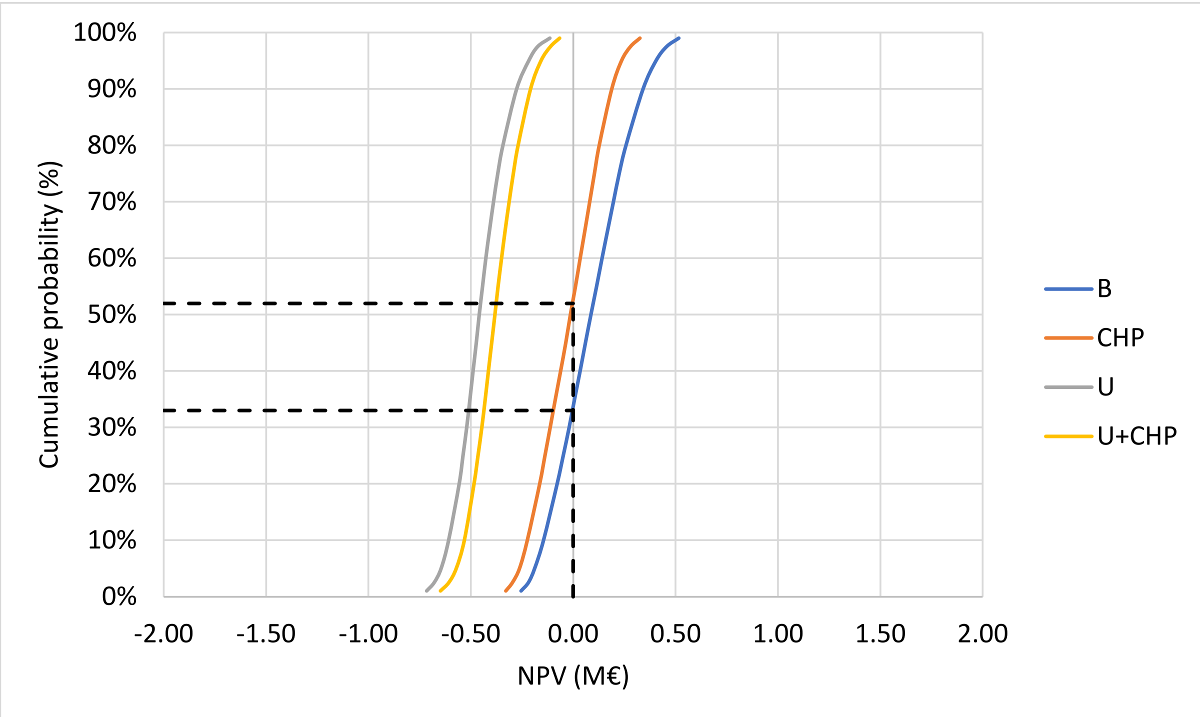

Figure C.16 Cumulative distribution function of the Net Present Value for the 4 biogas-end use configurations for a herd size of 60.

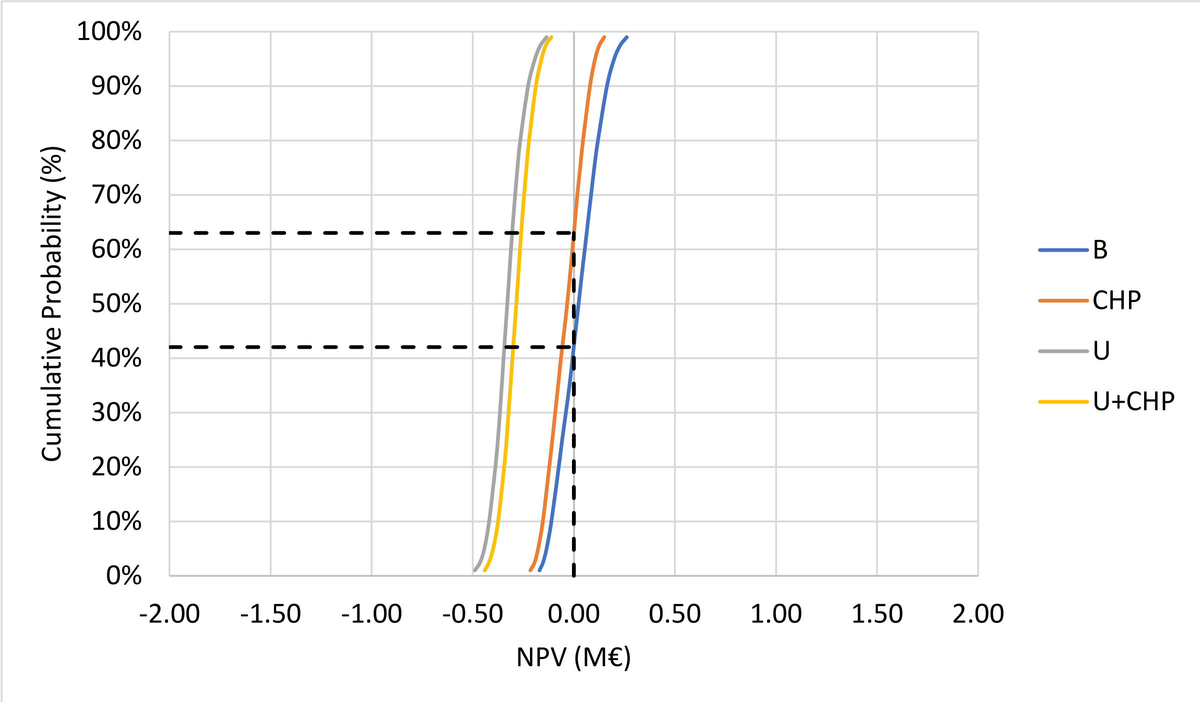

Figure C.17 Cumulative distribution function of the Net Present Value for the 4 biogas-end use configurations for a herd size of 40.

Appendix C.5

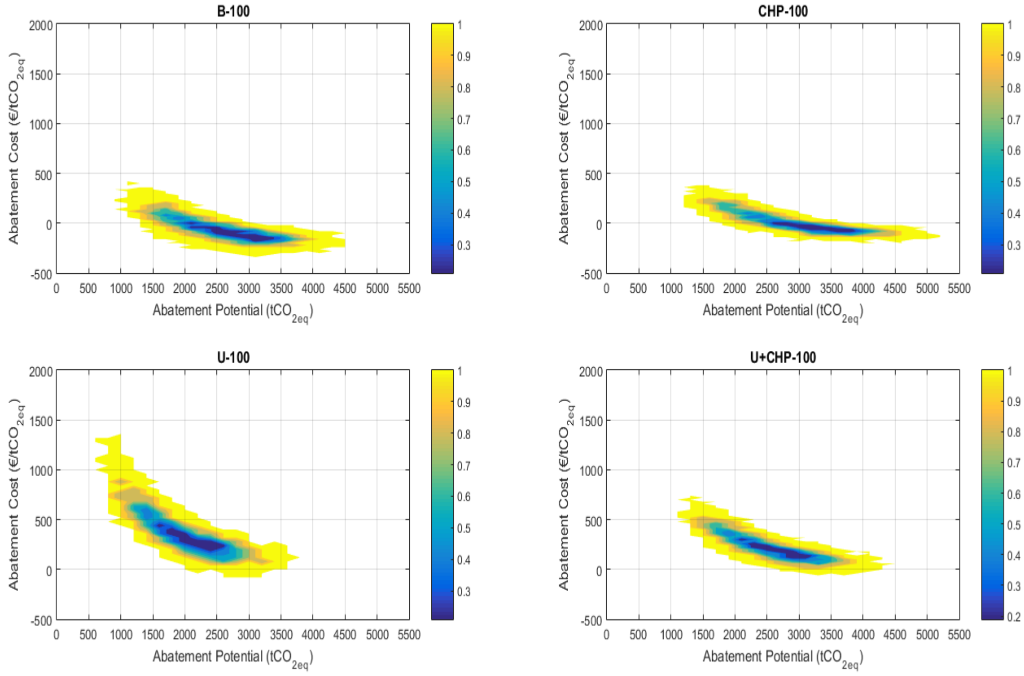

Figure C.18 Probability chart for different confidence interval ranges of abatement cost and abatement potential of different on-farm AD systems for a heard size of 100 accounting for uncertainty. The colour band delimits the probability of a result from a 100% probability (yellow) to a 20% probability (blue) of the scenario to achieve the delimited range of abatement cost and potential.

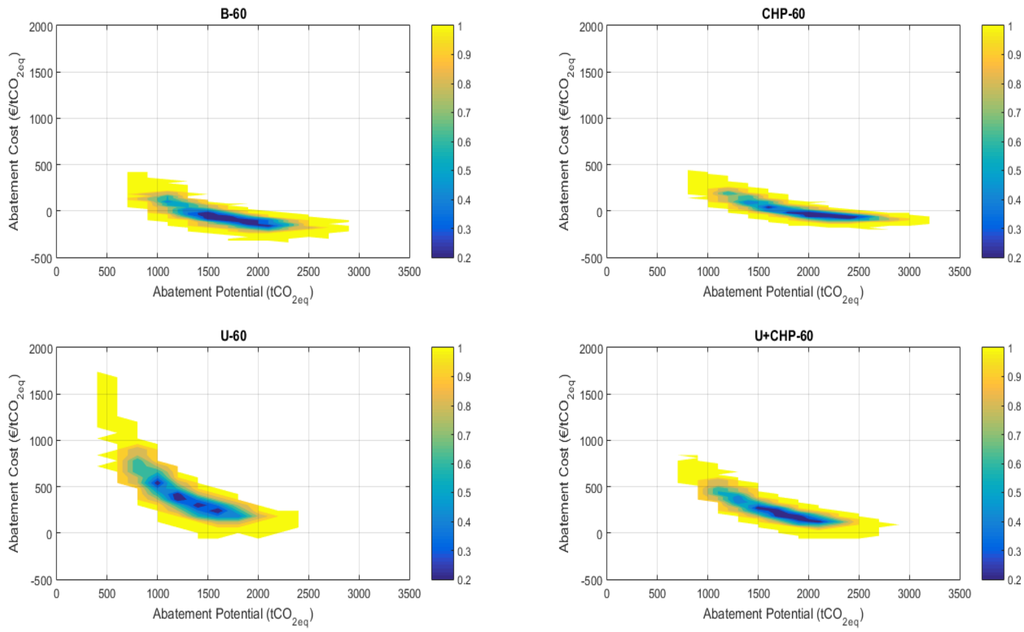

Figure C.19 Probability chart for different confidence interval ranges of abatement cost and abatement potential of different on-farm AD systems for a heard size of 60 accounting for uncertainty. The colour band delimits the probability of a result from a 100% probability (yellow) to a 20% probability (blue) of the scenario to achieve the delimited range of abatement cost and potential.

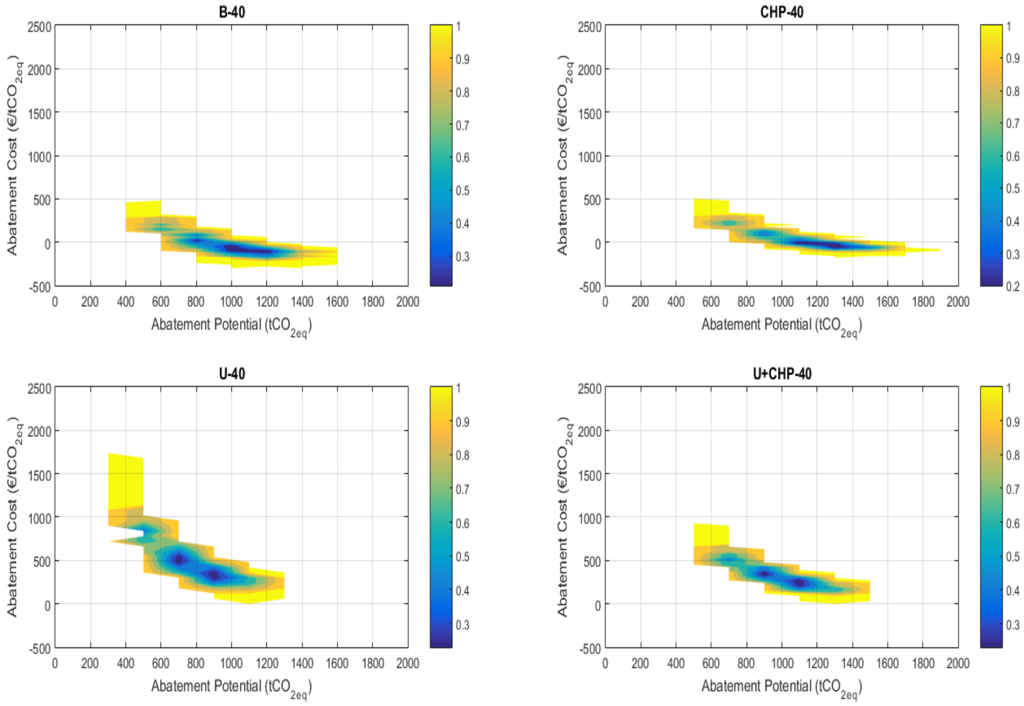

Figure C.20 Probability chart for different confidence interval ranges of abatement cost and abatement potential of different on-farm AD systems for a heard size of 40 accounting for uncertainty. The colour band delimits the probability of a result from a 100% probability (yellow) to a 20% probability (blue) of the scenario to achieve the delimited range of abatement cost and potential.

Appendix D

Appendix D.1

To calculate the reciprocating compressor power required in kW a reciprocating compressor calculator from CheCalc was used (1). This application estimates the overall power required based on input data from the gas mixture and the compressor data. For the calculations, the properties of biogas were based on an overall concentration of 60%$_{vol}$ of methane with the remainder 40%$_{vol}$ of the mixture assumed to be carbon dioxide. The input data for the gas can be found in table D-1 and for the compressor in table D-2.

Table D-1 Physicochemical properties for the biogas mixture for compression from the AD plants to a centralised unit.

Gas Data		
Parameter	**Unit**	**Source**
Inlet Pressure	1.013 bar	(1)
Temperature	15 °C	(1)
Outlet Pressure	1.163 bar	(1)
Gas Flowrate at compressor inlet	0.82 $m^3 s^{-1}$	(Based on the maximum flow rate of the biogas AD plants)
Critical Pressure	42.3 bar	(2)
Critical Temperature	82.5 °C	(2)
Acentric Factor	0.228 ω	(2)
Molecular Weight	16.04	(2)
cp cv^{-1} ratio	1.307	(3)

Table D-2 Technical properties for the reciprocator compressor for the AD plants to a centralised unit

Compressor Data		
Parameter	**Unit**	**Source**
Number of Stages	1	(4)
Polytropic Efficiency	80 η_{Poly}	(4,5)
Interstage Pressure drop	0.15 bar	
Intercooler	No	(5)
Mechanical Efficiency	97 η_{Mech}	(5)
Compression Ratio	Equal	Assumed

Appendix D.2

Table D-3 Operational cost of the AD-UF scenario for the 10 AD plants.

AD plant	Fixed Operating Costs	Electricity Cost	Feedstock Cost	Transmission Cost
1	€46,792	€37,866	€131,297	€6,061
2	€44,526	€34,814	€120,134	€5,572
3	€42,264	€31,766	€108,984	€5,084
4	€40,001	€28,718	€97,835	€4,597
5	€37,734	€25,665	€86,666	€4,108
6	€35,568	€22,747	€75,992	€3,641
7	€33,301	€19,694	€64,823	€3,152
8	€31,038	€16,646	€53,674	€2,664
9	€28,776	€13,598	€42,524	€2,177
10	€26,509	€10,545	€31,356	€1,688
Totals	€366,509.87	€242,061.02	€813,284.69	€38,744.07

Table D-4 Operational cost of the AD-CUP scenarios for the 10 AD plants.

AD plant	Fixed Operating Costs	Electricity Cost	Feedstock Cost
1	€11,449.92	€50,442.64	€131,321.24
2	€11,063.95	€49,534.62	€120,133.63
3	€10,677.98	€48,629.69	€108,984.07
4	€10,292.01	€47,724.76	€97,834.51
5	€9,906.04	€46,818.29	€86,665.93
6	€9,536.15	€45,951.97	€75,992.04
7	€9,150.18	€45,045.49	€64,823.45
8	€8,764.20	€44,140.56	€53,673.89
9	€8,378.23	€43,235.63	€42,524.34
10	€7,992.26	€42,329.16	€31,355.75
Totals	€97,210.91	€463,852.83	€813,308.85

1. Ó Céileachair D. SNAP input parameters and results [Internet]. Vol. 1. Mendeley Data; 2023 [cited 2023 Oct 23]. Available from: https://data.mendeley.com/datasets/5vkjkh8c6z/1

2. Cruz-Monterrosa RG, Bribiesca JER. Biomethane production. 2022;

3. Bauer F, Hulteberg C, Persson T, Tamm D. Biogas upgrading-Review of commercial technologies; Biogasuppgradering-Granskning av kommersiella

tekniker. 2013 [cited 2022 Jun 15]; Available from:
https://www.osti.gov/etdeweb/biblio/22090519

4. Aspelund A. Gas purification, compression and liquefaction processes and technology for carbon dioxide (CO2) transport. In: Developments and Innovation in Carbon Dioxide (CO2) Capture and Storage Technology. Elsevier; 2010. p. 383–407.

5. Carranza-Abaid A, Wanderley RR, Knuutila HK, Jakobsen JP. Analysis and selection of optimal solvent-based technologies for biogas upgrading. Fuel. 2021 Nov;303:121327.