Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT TEMPLATE

SECTION 1: PROJECT DETAILS – FOR PUBLICATION

Project Title	Developing Economic Solutions for on-farm Anaerobic Digestion technologies under Irish conditions (EcoAD)
Lead Grantee (Organisation)	University College Cork, MaREI Centre
Lead Grantee (Name)	Professor Jerry Murphy
Final Report Prepared By	Dr David Wall, Prof Jerry Murphy, Dr Richard O'Shea, Dr Xue Ning
Report Submission Date	H2 2023

	Name	Organisation
Project Partner(s)	Dr David Wall Dr Richen Lin Dr Richard O'Shea	University College Cork, MaREI Centre
Collaborators		

Project Summary (max 500 words)

Ireland must transition to a sustainable, renewable energy economy. Agriculture remains the largest contributor to greenhouse gas (GHG) emissions at ca. 37% of total emissions. On-farm anaerobic digestion (AD) to produce biogas and biomethane can contribute to greening agriculture and decarbonise heat and transport. The Irish Climate Action Plan outlines a goal of 5.7TWh of biomethane by 2030. However, conventional AD systems may suffer from high cost and low process efficiency, thus hindering commercial application at small-scale. The EcoAD project investigated economic solutions for future on-farm AD technologies using farm-based feedstocks (slurries, grass). Finding the most efficient and cost-effective production scenarios is of relevance in transitioning to a low carbon economy. The EcoAD project undertook the following research:

(1) Enhance on-farm digestion efficiency through novel pre-treatments.
Specific pre-treatments (biological acidification and hydrothermal hydrolysis) were applied to on-farm feedstocks to assess the potential for enhanced methane production. Temperature phased AD systems and biochar addition enhanced methane production. An energy conversion efficiency of 96% was recorded in two-stage digestion with biochar.

(2) Integration of electro-methanogenesis with anaerobic digestion to increase overall biomethane conversion.
The integration of novel bio-electrochemical systems with AD, namely the microbial electrolysis cell (MEC-AD) and microbial electro synthesis (MES-AD), was investigated as a means of increasing methane content in biogas and thus reducing biogas upgrading costs. The MEC-AD system promoted biomethane production and obtained a 6-fold increase on electrical energy input. The construction of a 3D cobalt and nickel coated carbon felt cathode in a MES-AD reactor facilitated acetate and ethanol production, by providing pore-specific surface area and local active electron transfer sites.

(3) Optimising the logistics of on farm anaerobic digestion in Ireland.
Alternatives to gas grid injection are required for biogas/biomethane generated from decentralised biomass located at a distance from the gas grid. Rural farming regions are often considered decentralised but have suitable biomass for AD. Approximately 17% of the national on-farm biomass was located in excess of 15km from the gas grid but within 15km of a large industry energy user. Virtual pipelines may be used for AD in areas with limited gas grid infrastructure, however mobile biogas upgrading units present logistical challenges and increase routing emissions. Pasture-based farming systems, and the resultant lack of slurry in summer, were found to account for higher emissions (by 11 g CO_2-eq MJ^{-1}) in terms of the biomethane produced as compared to systems with year-round availability of slurry.

(4) Techno-economic analysis of potential on-farm anaerobic digestion pathways.
The financial viability of biogas/biomethane systems such as those proposed in EcoAD were evaluated. A sensitivity analysis highlighted the key parameters affecting the techno-economic performance of on-farm AD plants in Ireland. The abatement cost of on-farm AD systems varied based on the processes considered within the system boundary and ranged from -117 to +79 €/tCO_2eq for small scale systems. To make biogas upgrading financially viable at small scale, additional incentives and revenues streams are required, along with the integration of a CHP unit to meet the parasitic energy demand of the system.

Keywords (min 3 and max 10)	On-farm anaerobic digestion; biomethane; biological acidification; hydrothermal hydrolysis; biochar; technoeconomic analysis; decentralised biomass; logistics; electro-methanogenesis.

NB – Both Section 1 and Section 2 of this Final Report will be made publicly available in a Final Technical Report uploaded online to the National Energy Research Database.

By submitting this project report to SEAI, you confirm you are happy for Section 1 and Section 2 of this report to be made publicly available. If you wish to request edits to this section in advance of publication, please contact SEAI at EnergyResearch@seai.ie.

SECTION 2: FINAL TECHNICAL REPORT – FOR PUBLICATION (max 10 pages)

2.1 Executive Summary

The Irish agricultural sector is the largest contributor to national greenhouse gas (GHG) emissions accounting for ca. 37% of total emissions. Methods to reduce GHG emissions from agriculture in Ireland are required in the short term. A target of 25% reduction in agricultural emissions has been introduced. On-farm anaerobic digestion (AD) can provide a renewable, sustainable fuel (in the form of biogas and biomethane) that can decarbonise the energy system and reduce emissions from the agricultural sector. Specifically, on-farm AD is viewed as a technology that can 'green' agriculture and assist in broader decarbonisation objectives in heat and transport. The Irish Climate Action Plan states that 5.7TWh of biomethane should be realised by 2030.

Ireland has a significant resource of grass silage and cattle slurry, these feedstocks can enable a large AD industry in the country. However, problems currently exist in the mobilisation and use of such feedstocks. For instance, grass and slurry are typically located in rurally dispersed regions away from existing gas grid infrastructure. Furthermore, cattle in Ireland spend the majority of the year outdoors in pasture-based farming systems, leading to intermittent slurry collection on farms. Access to and the seasonality of feedstock must be considered when mobilising an AD industry nationally in Ireland. Despite being a mature technology, conventional anaerobic digestion systems often suffer from high cost and low efficiencies, thus hindering commercial application. Novel technologies must be advanced to increase the efficiency of the AD process and reduce system costs particularly at small-scale. New approaches to the delivery of energy (biogas and biomethane) to the end user must also be developed, particularly in regions with limited gas grid access. Methodologies for biogas pipelines or mobile upgrading units in a virtual pipeline must be assessed. Ultimately, the economic viability of AD systems, taking all of the above factors into consideration, must be evaluated in detail.

The EcoAD project outlines economic solutions for future on-farm anaerobic digestion technologies using typical Irish farm-based feedstock (slurries, grass silage). Finding the most efficient and effective biogas and biomethane production scenarios is of relevance in transitioning to a low carbon economy. This project assessed three key aspects in relation to small-scale on-farm AD in Ireland: Logistics, Technology and Economics.

The logistical characteristics investigated included the on-farm biomass resources available in Ireland and its specific location with respect to both gas grid infrastructure and large industry energy users. Furthermore, the impact of seasonal feedstock availability and seasonal gas demand on on-farm AD plants was explored. Finally, the logistics of developing virtual biomethane pipelines and biogas pipelines serving on-farm AD plants were considered with a view on how to optimise these systems.

Novel technologies such as the microbial electrolysis cell (MEC) and microbial electrosynthesis (MES) were combined with traditional AD reactors to facilitate future cascading bioeconomy systems focused on advanced biofuel production. Furthermore, the effect of adding conductive materials to AD reactors to increase the activity of microbial communities was explored. The potential of biochar supplementation to boost biogas yields from on-farm feedstocks of grass and slurry was investigated. Finally, dual metal (Co and Ni) modified graphite electrodes were developed for upgrading CO_2 in the biogas into valuable chemical products (such as acetic acid and ethanol) in a microbial electrosynthesis system.

Economic viability was primarily assessed through a techno-economic analysis. Marginal abatement cost curves (MACCs) were used to compare the cost of GHG mitigation. Biogas and biomethane from anaerobic digestion in an agricultural setting were previously evaluated using a single high cost of abatement. Single cost values for abatement cost may not capture the variable nature of AD systems. Thus, more detailed abatement costs were developed that considered varying system boundaries and key variables values such as additional revenue streams (such as sale of biofertiliser), displaced energy savings, and additional incentives and emissions savings from co-benefits. Monte Carlo analysis was run to generate probability charts that visually indicated the most sensitive input variables that influenced the financial viability and the environmental performance of AD systems.

Some of the key learning outcomes of the EcoAD project are listed here:

- A substantial quantity of the national on-farm biomass (17%) is located in excess of 15km from the gas grid but within 15km of a large industry energy user.
- The current Irish on-farm biomethane resource is approximately 200% of industrial natural gas use.
- Pasture-based on-farm AD systems increase biomethane production emissions by 11 g CO_2-eq MJ^{-1} compared to zero grazing systems.
- Virtual biomethane pipelines may be facilitate biomethane transportation in areas with limited gas grid infrastructure.
- Mobile biogas upgrading units present logistical challenges and their higher routing emissions can impact biomethane sustainability.
- Biochar addition enhances hydrolysis, acidification, and methane production in anaerobic digestion.
- A microbial electrolysis cell (MEC) AD system can increase biomethane output by 6-times the input electrical energy demand.
- The abatement cost of AD systems varies based on the processes considered within the system boundary.
- On-farm anaerobic digestion abatement costs ranged from -117 to +79 €/tCO_2eq for small scale systems.
- The production of electricity and heat in a biogas fuelled CHP unit had a higher probability of achieving lower abatement costs.
- To make biogas upgrading financially viable at small scale, additional incentives and revenues streams are required, along with the integration of a CHP unit to meet the parasitic energy demand of the system.

2.2 Introduction to Project

Decarbonising Ireland's natural gas network and agricultural sector are both essential to fulfilling the country's climate obligations. Shortfalls in targets for renewable energy in heat (RES-H) and renewable energy in transport (RES-T) of 3.2% and 5% (of their 12% and 10% targets, respectively) were reported in 2020. Anaerobic digestion (AD) provides an important means by which Ireland's abundant agricultural biomass resources could be utilised to produce sustainable, renewable gas (biogas and biomethane) for the heat and transport sectors whilst also reducing agricultural-related GHG emissions. A recent target of a 25% reduction in GHG emissions from agriculture has been established for 2030 by the Department of the Environment Climate and Communications; it is thought that AD can play a key role in this undertaking. The Irish Climate Action Plan also targets 5.7TWh of biomethane by 2030.

Ireland has a unique opportunity to establish a significant on-farm AD industry by leveraging our intrinsic expertise in the growing, harvesting, and storing of grass, and co-digesting with our abundant resource of cattle slurry. On-farm anaerobic digestion for the production of biomethane can contribute to greening agriculture and broader decarbonisation in heat and transport. However, conventional anaerobic digestion systems for biomethane production may suffer from high cost and low digestion efficiency, thus hindering commercial application. The EcoAD project intends to develop economic solutions for future on-farm anaerobic digestion technologies using typical Irish farm-based feedstock (slurries, grass silage).

Finding the most efficient and cost effective biomethane production scenarios is of relevance in transitioning to a low carbon economy.

The EcoAD project proposed to undertake research on the following four topics:

1. Enhance on-farm digestion efficiency through novel pre-treatments.
2. Integration of electro-methanogenesis with anaerobic digestion to increase overall biomethane conversion.
3. Optimise the logistics of on farm anaerobic digestion in Ireland.
4. Conduct techno-economic analyses of potential on-farm anaerobic digestion pathways.

Ultimately this project will inform future best practices and assess the economic viability of on-farm biomethane production from novel integrated anaerobic digestion systems.

2.3 Project Objectives

No:	Objective Description:
1.	Investigate use of novel pre-treatments and multiphase digestion technologies to increase energy production from agricultural feedstock
2.	Explore further digestate valorisation with the production and use of biochar in novel digester systems to increase AD efficiency
3.	Assess optimal routes for on-farm AD in the energy market in Ireland
4.	Provide TEA of the most promising on-farm AD deployment pathways
5.	Effective dissemination of the EcoAD project through detailed Communication Plan (including IEA Bioenergy Task 37 platform)

2.4 Summary of Key Findings/Outcomes

WP1 Enhance on-farm digestion efficiency through novel pre-treatments: A literature review on biomass pre-treatment technologies was completed (WP1-D1). Batch experiments of biological acidification and hydrothermal hydrolysis were conducted. A paper titled "Biochar facilitates biohydrogen and biomethane production through batch single-stage and two-stage digestion of grass silage and cattle slurry" was published in the *Journal of Cleaner Production* (WP1-D2). The output from the batch experiments informed the design of continuous biological acidification experiments. A paper titled "Improving biomethane production from biochar-supplemented two-stage anaerobic digestion of on-farm feedstocks" was published in the *Journal of Cleaner Production* (WP1-D3).

WP2 Integration of electro-methanogenesis with anaerobic digestion to increase overall biomethane conversion: The integration of anaerobic digestion with three emerging bio-electrochemical technologies in a circular cascading bioeconomy was assessed: (1) AD-power to gas (AD-P2G), (2) AD-microbial electrolysis cell (AD-MEC – see Figure 1), and (3) AD-microbial electrosynthesis (AD-MES). The processes, advantages, and challenges of different systems were summarised to inform the design for improved process sustainability. A paper titled "Emerging bio-electrochemical technologies for biogas production and upgrading in cascading circular bioenergy systems" was published in *iScience* (WP2-D1). A paper titled "Improving the efficiency of anaerobic digestion and optimizing *in-situ* CO_2 bioconversion through the enhanced local electric field of microbe-electrode interface" is under review in *Renewable and Sustainable Energy Reviews* (WP2- D1/D2). This paper investigated modelling and improving direct interspecies electron transfer by biochar supplementation in integrated microbial electrolysis cell and anaerobic digestion (MEC-AD) reactor. A further paper titled "Tip-enhanced electric field to facilitate microbe-electrode interaction on the biocathode of microbial CO_2 electrosynthesis" is ready for journal submission (WP2-D1/D2).

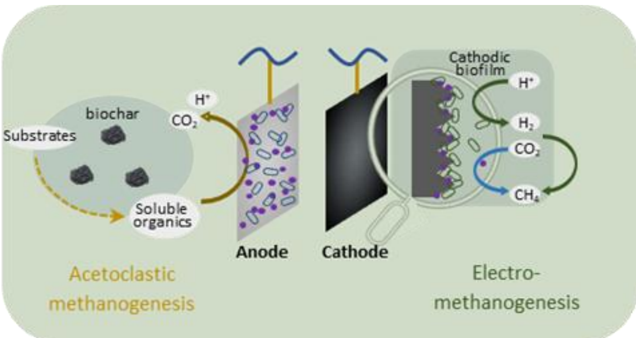

Figure 1 The mechanism of microbial electrolysis cell

WP3 Optimising the logistics of on farm anaerobic digestion in Ireland: A literature review was conducted on the use of on-farm resources for AD (WP3-D1). GIS maps were developed to identify the resource of decentralised biomass suitable for use in AD in Ireland (see Figure 2) (WP3-D2). A paper was published in the *Applied Energy* journal that analysed the range of options available for on-farm AD in Ireland and looks at how best to utilised decentralised on-farm biomass resources (WP3-D4). An Excel tool was developed to examine the effects of slurry seasonality and gas demand seasonality on on-farm AD plant operation. A paper on this work was published in the *Journal of Cleaner Production* (WP3-D1/D4). In collaboration with researchers in MTU, a paper was published on virtual biomethane pipeline models in the *Journal of Cleaner Production* (WP3-D3). The paper investigates the logistics of biomethane transportation via a virtual biomethane pipeline optimisation model serving on-farm AD plants using vehicle routing problem techniques and includes for a mobile-upgrading and compression unit (WP3-D3). A GIS model was developed to optimise the layout of biogas pipelines which serve a central biogas user either via minimum spanning tree or by the road network (WP3-D2). Heuristics were developed to decide on which plants, and therefore which layout, provided the optimal asset utilisation efficiency (biogas-to-pipeline ratio). A paper is currently under review with the journal *Fuel*.

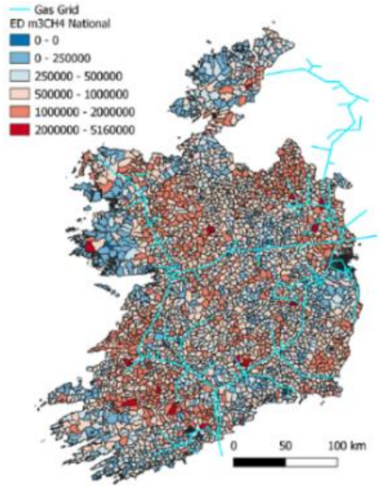

Figure 2 GIS Maps used to assess logistics and optimise the resource of on farm AD

WP4 Techno-economic analysis of potential on-farm anaerobic digestion pathways: A literature review of previous methodologies used for the techno-economic analysis (TEA) of on-farm AD was completed (WP4-D1). A manuscript titled "*A perspective on methodologies and system boundaries to develop abatement cost for on-farm anaerobic digestion"* was published in the journal *Bioengineered*. This paper reviews the current methodology used to calculate the abatement cost for AD and compares it to the Marginal Abatement Cost Curve (MACC) values in the Irish Climate Action Plan. A TEA and lifecycle assessment (LCA) was carried out for on-farm AD systems to compare the abatement cost of AD systems at a range of scales. A paper titled *"Assessing the cost variability of emissions abatement in small-scale on-farm anaerobic digestion"* has been published in the journal *DeCarbon* (see Figure 3) (WP4-D4). A combined analysis tool that integrates TEA and LCA, sensitivity analysis and uncertainty analysis was developed to identify the relevant inputs and outputs that directly impact the abatement cost (WP4-D2). The software @Risk (provided by Lumivero) was used to integrate the sensitivity and uncertainty analysis. A manuscript titled *"Probabilistic analysis of the abatement cost and potential of on-farm anaerobic digestion in Ireland"* has been written as a thesis chapter with the future intention to submit to a journal. A manuscript titled *"The economic impact of novel enhancement performance technologies and biogas logistics for on-farm AD*" is currently being developed, and will economically assess baseline and novel on-farm AD systems using the TEA tool developed (WP4-D3).

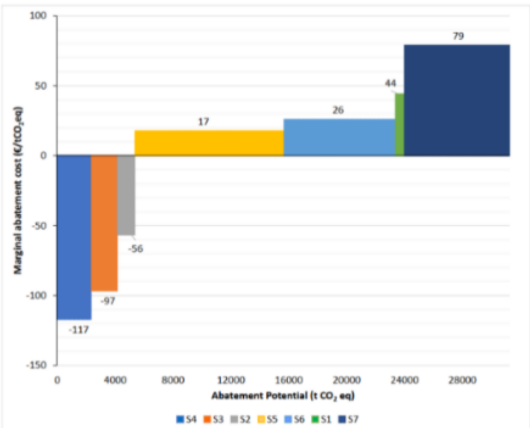

Figure 3 Marginal Abatement Cost Curves for small and medium scale on-farm AD systems

WP5 Management, communication and dissemination: The project was added to the Environmental Research Institute (ERI) and MaREI websites. A branding logo was developed for the EcoAD project. Dr Wall, Prof Murphy and Dr O'Shea have participated in and presented at various IEA Bioenergy Task 37 meetings and events (in Switzerland, Australia, Sweden, India) and the EcoAD team have authored three IEA Bioenergy reports (see Section 3). EcoAD steering group meetings took place in 2021 and 2022 including stakeholders from Gas Networks Ireland, SEAI, Teagasc and the Department of Agriculture. These meetings included for project team presentations, discussion and feedback. The EcoAD team attended and presented at numerous conferences including the SEAI National Energy Research & Policy Conference; the Nordic Biogas Conference; the Anaerobic Digestion Webinar for the Dingle Peninsula; Environ and 4th International Conference for Bioresource Technology for Bioenergy, Bioproducts & Environmental Sustainability. Annual reports have been submitted to the SEAI for the project (WP5-D2). An article was published on RTÉ Brainstorm on the findings of the project and we have been interviewed on RTÉ Raidió na Gaeltachta. The EcoAD team met with the Minister for the Environment to discuss the project and the development of the Irish AD sector.

- Innovation 1: **Competing reactions limit the efficacy of hydrothermal hydrolysis of grass**:
  The optimal conditions for hydrothermal hydrolysis pre-treatment (140°C for 20 min) of grass silage showed the highest sugar yield (0.29 g/g volatile solid).
- Innovation 2: **Biochar can facilitate hydrolysis and methanogenesis**
  Biochar supplementation of 10 g/L is optimal in two-stage anaerobic co-digestion of grass silage and cattle slurry. Biochar can; increase the system buffering capacity to alleviate VFA accumulation, immobilise functional microorganisms, and support direct interspecies electron transfer.
- Innovation 3: **Integration of renewable electricity and AD for advanced gaseous transport biofuels production**
  The roles of three emerging circular cascading systems were assessed when combined with AD: power to gas (P2G); the microbial electrolysis cell (MEC); and microbial electrosynthesis (MES). Energy production scenarios were evaluated based on state-of-the-art research and the integrated microbial electrolysis cell with AD was identified as the optimal biomethane production scenario in terms of energy yield per unit feedstock.
- Innovation 4: **The MEC-AD system increased biomethane production and obtained a 6-fold increase on the electrical energy input**
  The MEC-AD system with the modified cathode converted 40.7% of the energy input (biomass, thermal and electrical) to methane. A conventional AD reactor converted 21.5% of the energy input (biomass and thermal) to methane. The electricity input to the MEC-AD system in essence acted as a catalyst. A 6-fold return on the electricity input was generated in the form of extra biomethane.
- Innovation 5: **Over 17% of national on-farm biomass is in excess of 15km from the gas grid but within 15km of industry**
  The location of on-farm biomass resources and their proximity to the gas grid was evaluated using GIS mapping at an electoral district level. An origin destination matrix indicated the percentage of the theoretical on-farm biomethane resource that could be captured at various distances away from the gas grid and within a specific distance of a large industry energy user (LEU).
- Innovation 6: **On-farm biomethane resource equates to 200% of industry gas use in Ireland**
  The biomethane potential of all on-farm biomass in Ireland was calculated at 67 PJ. Industry natural gas usage is 33 PJ annually.
- Innovation 7: **Industry heat demand can be met by biomethane produced within 2.5km of large energy user**
  Two large energy users (LEUs) were analysed as case studies. The on-farm biomethane resource within 2.5km of those LEUs could be utilised to meet the entire thermal demand of those LEUs.
- Innovation 8: **Abatement cost depends on the specific system boundary for on-farm AD**
  On-farm AD abatement costs ranged from -117 to 79 €/tCO_2eq. The use of the by-products (CO_2, biofertilizer) and the processes considered within the system boundary had significant impact on the abatement cost.
- Innovation 9: **Additional incentives and sources of revenue streams for on-farm AD systems can lower the abatement cost**
  The abatement cost of different on-farm AD systems based on the biogas end-use ranged between -7 to 816 €/tCO_2eq. It was shown that an increase in tariffs and biomethane sale prices could substantially improve the financial viability of the systems thereby reducing the abatement cost from +72 to -227 €/tCO_2eq.

- Innovation 10: **Pasture-based farming systems increase emissions from on-farm AD systems compared to zero grazing systems.**
  The availability of slurry only during winter (pasture-based farming) may increase biomethane production related emissions by 11 g CO_2-eq MJ^{-1}. Methane losses are crucial for sustainability criteria with seasonal slurry availability.
- Innovation 11: **Virtual biomethane pipelines and physical biogas pipelines optimisation**
  Vehicle routing problem techniques were used to design several virtual pipelines to serve 100 AD farms. GIS software was used to optimise the layout of biogas pipelines serving 10 AD plants via a minimum spanning tree or by following the road network.

2.5 Project Impact

Meeting National and Global Challenges

There are ever expanding targets for renewable energy from biogas and biomethane. Ireland has a target of 5.7 TWh of biomethane by 2030 in the 2023 Climate Action Plan. The REPowerEU plan has a target of 35 billion cubic metres of biomethane to be produced in the EU by 2030, over 10 times the existing production. To meet these targets several barriers must be overcome. Specifically, logistics must be considered in the development of on-farm anaerobic digestion (AD) in Ireland, as a way of producing sustainable biogas and biomethane from on-farm feedstocks, providing an alternative to fossil fuels. The considerations that are studied in this project included: the decentralised resource and lack of gas grid access across rural areas of the country; the seasonal availability of cattle slurry as a feedstock; the implications of possible seasonal gas demand profiles amongst decentralised large energy users (LEUs); and how virtual biomethane pipelines or physical biogas pipelines would serve as energy delivery methods. The results of the EcoAD analysis showed that the biomethane resources available from on-farm feedstocks in Ireland are significant and furthermore, informed decisions can now be made on how the industry should emerge nationally.

The focus on novel technologies in the EcoAD project explored the synergistic integration of anaerobic digestion and bio-electrochemical technologies in cascading circular bioeconomy systems. Simultaneously enhanced biogas production and CO_2 upgrading can be achieved through efficient direct interspecies electron transfer by adding biochar and/or by imposing an external electricity supply. This research increases the technology readiness level (TRL) of these novel technologies, and the data generated in the project can provide guidance on designing future cascading circular bio-systems to produce advanced biofuel and value-added chemicals. The optimal system assessed in this project (a microbial electrolysis cell integrated with anaerobic digestion using a modified graphite cathode) enhanced overall biomethane yield by 98% as compared to conventional anaerobic digestion. This could reduce the feedstock required for biomethane targets such as REPowerEU by a factor of 2.

In essence, the EcoAD project promotes renewable technologies in more-sustainable agriculture practices, through for example, the production of sustainable, renewable fuels for heat and transport, and methods for climate mitigation, all of which are objectives outlined in the National Implementation Plan for the Sustainable Development Goals 2022-2024 (DCCAE, 2018). Furthermore, the EcoAD project demonstrated the circular economy approach to energy production in an agricultural setting, which is of significant importance as outlined in the National Development Plan 2021-2030 and the Whole of Government Circular Economy Strategy 2022 – 2023. The fundamental pathways developed for on-farm AD systems in Ireland generate a range of societal, scientific and economic impacts that support international, EU and Irish policy and research priorities.

Economic, Societal and Environmental Impacts

The EcoAD analysis included for a comprehensive economic feasibility analysis of on-farm AD. This information can be used by stakeholders and policymakers to deliver cost-effective on-farm AD systems nationally. The development of such projects would benefit Ireland in terms of job creation in rural areas, and particularly in diversifying revenue in the agricultural sector. Renewable and sustainable energy applications will directly benefit the rural economy; creating jobs in remote areas and reversing rural depopulation, providing diversification and stabilisation of farm incomes to farmers thereby contributing to the aims set in the Irish Government's Rural Development Policy 2021-2025.

The ability of on-farm AD to enhance Ireland's security of energy supply and facilitate the move away from a fossil-based energy supply was demonstrated in the EcoAD project through case studies on large industry energy users in decentralised areas. This aligns with the priority of reducing fossil fuel use and enabling climate mitigation as described in Ireland's Climate Action Plan. An indigenous energy supply could increase Ireland's energy security. Facilitating the creation of a biogas industry would also create a greater awareness of the significant bioresources available to the citizens of Ireland, and subsequently encourage the public to use renewable energy.

Benefits to Industry

The work packages in the EcoAD project have provided a detailed characterisation of cost-effective AD systems that could be developed in Ireland. The analysis directly increases the competitiveness of the biogas industry in Ireland and may alleviate some of the technical and financial barriers that have been experienced to date. The modelling of optimal biogas pipeline configurations for transporting biogas to end users, and modelling of optimal routes for mobile upgrading systems will facilitate the production of renewable energy in the form of biogas/biomethane in Ireland. The project also promotes initiatives in 'greening' agriculture, industry and transport and ultimately should stimulate future policy development and support for AD nationally.

Additionally, the novel technologies (microbial electrolysis cell integrated with anaerobic digestion) developed in this project will advance their deployment. By developing new technologies, providing research-based data, and bringing stakeholders together in a series of workshops (including IEA Bioenergy dissemination), the project provided an evidence-based approach to the benefits of anaerobic digestion within a circular economy.

Benefits to Research Excellence and Leadership

The project funded three PhD students (2 males and 1 female) in environmental and energy engineering. The EcoAD project enhanced the research capacity, research excellence and international engagement for the three students. Specifically, EcoAD allowed them to engage with industry and policy makers, and advance their scientific understanding of key topics, establishing them as future research leaders. Following project completion, one of the PhD students now works for Ireland Strategic Investment Fund (ISIF) in developing the biomethane sector in Ireland; one student has remained in the research group as a postdoctoral researcher to continue the development of novel AD systems; and the third student plans to start work in Teagasc as a postdoctoral researcher in late 2023. The EcoAD project has also provided a platform to potentially leverage further funding in AD for the project leads.

Eight academic papers were published in high impact scientific journals and 2 further papers are under review. Academic outputs reached international audiences via the peer-review literature and the existing networks provided by the SFI MaREI centre for energy, climate and marine and the International Energy Agency (IEA) technology collaboration programme (TCP) in Bioenergy.

2.6 Recommendations

Recommendations for future research

- More research is required on the microbial electrolysis cell-anaerobic digestion (MEC-AD) system. The technology readiness level is currently 5. It is recommended as an effective approach to enhance biomethane conversion as compared to conventional anaerobic digestion. The electricity input to the MEC-AD system facilitates increased energy output from the overall system with a 6-fold increase in energy output per unit of electrical energy input. However, the MEC-AD system may face operational challenges in achieving long-term steady biomethane production. The performance of the MEC-AD system is significantly affected by internal electrochemical factors, such as the cathode material, cathode potential and current density. Reactor design and precise process controls need to be further investigated to ensure the optimal operation of the MEC-AD system.
- Additional research is needed on the application of microbial electrosynthesis which shows great potential when operating on its own or when combined with anaerobic digestion to produce desired products. In the anaerobic digestion-microbial electrosynthesis system, biochemical processes of organic substrate degradation and CO_2 biomethanation can be physically separated to ensure system stability. In addition to the CO_2 in biogas, other sources of CO_2 such as from food and beverage industries can be used to increase the system flexibility and capacity in a CO_2 biorefinery based on the microbial electrosynthesis process. Such routes should be explored further.
- The CO_2 biorefinery may be improved by efficient electron transfer between electrodes and microorganisms in a cascading bio-electrochemical system. It is recommended that biocompatible electrodes are developed to stimulate the growth of electroactive biofilms on the cathodic interface. Further research on surface characteristics of the abiotic cathode, electrochemical properties of the domesticated biocathode and the composition of the biofilm would support in understanding

the mechanism electrode-microorganism interactions, and facilitate the optimisation of microbial electrosynthesis to produce multi-carbon products.

- The biomethane resource available from on-farm biomass in Ireland is significant. Co-digesting slurry and surplus grass would be the most viable option for on-farm AD in Ireland. A push towards the use of slurries as opposed to grass in AD would alleviate sustainability concerns but may also lead to a lower energy production. Further research should investigate as to whether on-farm AD systems fed with slurry-only would be feasible in Ireland.
- Improved resource and spatial analyses are recommended to determine co-location of feedstocks with either gas grid infrastructure or access to industry end users.
- Whilst the work of this project focuses on grass silage as a biomass source, recent developments have suggested that multi-species swards may be a more sustainable option. Multi-species swards can improve on-farm biodiversity, require less nitrogen fertiliser, increase total grass output, and decrease absolute emissions. Future research should investigate the biomethane potential of multi-species swards, co-digestion potential with slurry, and sustainability implications.
- If seasonally available slurry is to be used as a feedstock, the changing chemical and nutrient composition of any digestate produced should be investigated.
- Potential improvements to mobile-upgrading and compression technologies should be further researched. Models for the optimum routing strategy (daily, weekly) of such mobile-upgrading units should be considered.
- Further research should investigate the total energy balance of biogas pipelines. Compression and parasitic demand requirements may be deciding factors in scenario feasibility from an energy perspective.
- The optimal AD plant size for the use of either virtual biomethane pipelines or biogas pipelines should be investigated. It is likely that due to logistics, capital costs, and/or technological limitations the size of AD plants in a potential network may dictate whether virtual pipelines or biogas pipelines should be employed.
- A full techno-economic analysis would reveal the feasibility of both virtual biomethane pipelines and biogas pipelines as proposed in the EcoAD project.
- Capital costs and thin margins may pose significant threats to the development of decentralised on-farm AD. Analysis should discern which policies could support decentralised AD and may include guaranteed feed-in-tariff rates or capital grants.
- Further multi criteria decision analysis using criteria such as land access barriers or labour costs may give further indication as to the best performing biogas pipeline layouts.

Recommendations for industry

- In continuous long-term operation, the incorporation of two-stage anaerobic digestion with biochar addition is a promising approach to enhance system stability and improve biomethane production. Two-stage anaerobic digestion is recommended as this process enhances hydrolysis and biohydrogen generation in the first stage, promotes biomethane production in the second stage, and improves system stability at higher organic loading rates.
- Biochar supplementation at an optimal dosage of 10 g/L is suggested in two-stage anaerobic co-digestion of grass silage and cattle slurry. Biochar increases the system buffering capacity to alleviate VFA accumulation, immobilizes functional microorganisms, and supports direct interspecies electron transfer.
- Emissions from agriculture represent over 37% of national greenhouse gas emissions in Ireland. The development of on-farm AD systems may lead to lower agricultural emissions through improved slurry management practices, whilst also promoting circular economy practices, decarbonisation, and improved energy security. This will benefit all agriculture industries across Ireland, and not just those in rural areas. The production of digestate as a secondary output to biomethane provides a local and sustainable alternative to synthetic fertilisers, that are less likely to see price fluctuations due to geopolitical events.
- The use of biogas and biomethane in Ireland will enable the reduction of emissions from heat, transport, and large energy users (LEUs), allowing industries to reduce their GHG emissions as required by governmental policies. Recent geopolitical crises have also emphasised the potential for biomethane to both decarbonise industries and improve energy security.

Recommendations for policy makers

- Ireland has a target of 5.7 TWh of biomethane by 2030. The REPowerEU plan has a target of 35 billion cubic metres of biomethane in the EU by 2030, more than 10 times current biomethane production. Questions are raised as to the sustainable biomass resource to support this. The optimal system assessed in this work (a microbial electrolysis cell integrated with anaerobic digestion using a modified graphite cathode) enhanced overall biomethane yield by 98% as compared to conventional anaerobic digestion. This could reduce feedstock requirement by a factor of 2 in meeting these targets.
- Research funding is required to increase the technology readiness level to facilitate the commercialisation of technologies and systems (such as those proposed in the EcoAD project) which optimise the integration of bio-electrochemical technologies with anaerobic digestion.
- The gross biomethane resource from dairy slurry and surplus grass silage is enough to satisfy over 150% of national industrial natural gas demand. In conjunction with the total national on-farm biomethane resources, rural areas with no gas grid access have significant biomethane resources in their vicinity. Rural communities are heavily reliant on fossil fuels for transport and heating – biomethane serves as a potential alternative which addresses decarbonisation and energy security concerns simultaneously. The development of on-farm AD would also allow farmers to reduce their methane emissions from current slurry management practices. This, in conjunction with the use of sustainable biomethane, would aid Ireland in meeting its COP26 climate obligations and the targets within the Climate Action Plan (CAP). The 5.7 TWh biomethane should see the construction of approximately 130 large-scale AD plants in Ireland by 2030 – there is no logistical reason that small-scale rural AD plants could not be built simultaneously in addition to the large-scale plants.
- Lack of gas grid access means that, with decentralised AD, a question arises as to who or what will use any biomethane produced, if electricity is not the desired output. Transport for Ireland (TFI) Local Link vehicles fuelled by biomethane would provide rural communities with sustainably fuelled public transport, whilst providing a reliable customer for on-farm AD plant operators and promoting circular economy practices.
- Sustainability concerns have been raised regarding the use of grass silage as an AD feedstock in recent times, especially when grass silage is used in high proportions relative to animal manures; the seasonal availability of slurry in Ireland increases this likelihood. If multi-species swards prove to be a more sustainable option that have lower fertiliser requirements, policies should be in place to facilitate their uptake amongst farmers.
- The abatement cost of AD systems varies based on the different processes considered within the system boundary. Single values should not be used to represent the abatement cost associated with on-farm anaerobic digestion as has been reported previously. A range of abatement costs have been reported in this project. Biogas for the production of electricity and heat in a CHP unit had a higher probability of achieving lower abatement costs. To make biogas upgrading financially viable at small scale, additional incentives and revenues streams are required and the integration of a CHP unit to meet the parasitic energy demand of the system.

2.7 Conclusions and Next Steps

The EcoAD project offered a bridge between science, industry, community engagement and policy. This project set out a series of objectives which are answered below:

Objective 1: Investigate use of novel pre-treatments and multiphase digestion technologies to increase energy production from agricultural feedstock

Continuous two-stage anaerobic digestion systems performed better than continuous single-stage systems. Biochar addition improved performance in both continuous single and two-stage anaerobic digestion systems. This was postulated as due to the pre-enhanced hydrolysis process and biochar-promoted methanogenesis process. In continuous trials, the 10 g/L biochar-supplemented second-stage reactor had the highest CH_4 yield of 237 L/kg VS at an organic loading rate of 4.0 g VS/L/d; this was 12% higher than that that achieved in the 10 g/L biochar-supplemented single-stage reactor (212 L/kg VS). The optimal system with the highest energy conversion efficiency of 96.5% was achieved (with an energy yield of 8.5 MJ/kg VS) in the two-stage digesters with 10 g/L of biochar supplement.

Objective 2: Explore further digestate valorisation with the production and use of hydrochar in novel digester systems to increase AD efficiency

Co-digestion of grass silage and cattle slurry was enhanced due to biochar addition in batch two-stage anaerobic digestion. The highest methane yield of 253 L/kg VS, (equivalent to a biodegradability index of 87%), was achieved with a 10 g/L biochar supplement. The interlaced conductive network established by extracellular polymeric substances and biochar promoted microbial electron transfer within the methanogenesis process.

The biomethane yield and biogas methane content from the integrated microbial electrolysis cell and anaerobic digestion (MEC-AD) system with a plain graphite cathode increased by 68% and 17% respectively, as compared to conventional anaerobic digestion when co-digesting grass silage and cattle slurry. Biochar supplement (10g/L) in the MEC-AD system can further increase biomethane yield by 9% as compared to the MEC-AD system without biochar addition. The reason for such an increase may be an enhanced anaerobic digestion process together with *in-situ* carbon conversion of CO_2 in the biogas to CH_4. *In-situ* CO_2 bioconversion was proposed to be enhanced at an applied voltage of 1.0 V in the MEC-AD system, as methanogenic archaea can use extra electrons provided by the electrode.

Objective 3: Assess optimal routes for on-farm AD energy market in Ireland

The total on-farm biomethane resource in Ireland was estimated to be 67 PJ a^{-1}. Approximately 17% of this resource is more than 15 km away from gas grid infrastructure whilst also within 15 km of a large industry energy user. Seasonal slurry availability on an Irish dairy farm can lead to a 21% reduction in total biomethane production, whilst increasing the carbon intensity of the biomethane produced (as compared to year-round availability) by 11 g CO_2 MJ^{-1}. Seasonal gas demands may be facilitated without significant effect on biomethane sustainability. Liquid digestate must be recirculated during times of no slurry availability to keep the solids content of the digester low enough to ensure sufficient mixing takes place. In the delivery of the energy to the end user, virtual pipelines serving on-farm AD plants may reduce the total transport requirements and associated GHG emissions by using larger biomethane haulage vehicles. The use of mobile-upgrading and compression units may be logistically unfeasible due to the slow upgrading speed of current technologies. Heuristics (practical methods to solve very complex problems) used in GIS software may be employed to quickly find optimal biogas pipeline layouts which either follow the shortest possible path (Steiner minimum spanning tree (MST)) or follow the road network. A road network pipeline layout connecting 10 AD plants to the biogas user costs 26% more than a Steiner MST would.

Objective 4: Provide TEA of the most promising on-farm AD deployment pathways

The economic viability of AD systems with grass silage and cattle slurry feedstocks were compared using different biogas end-use options (heat, electricity and biomethane) and varying farm size. The abatement cost and potential were obtained based on the net present value (NPV) and the total discounted GHG emissions for each system configuration. Biogas upgrading to biomethane was typically not financially viable due to the high operational and capital costs of small-scale upgrading systems. To make small-scale upgrading more attractive, additional incentives and revenue streams or the integration of a CHP unit to cover the energy demand of the system would be required. 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.

Objective 5: Effective dissemination of the EcoAD project through detailed Communication Plan (including IEA Bioenergy Task 37 platform)

The communication plan was successfully implemented for the project. The team participated in and presented at various IEA Bioenergy Task 37 meetings and events (in Switzerland, Australia, Sweden, India) and authored three IEA Bioenergy reports. Steering group meetings took place annually with stakeholders from Gas Networks Ireland, SEAI, Teagasc and the Department of Agriculture. Numerous conferences and workshops were attended such as the SEAI National Energy Research & Policy Conference; the Nordic Biogas Conference; the Anaerobic Digestion Webinar for the Dingle Peninsula; Environ and 4th International Conference for Bioresource Technology for Bioenergy, Bioproducts & Environmental Sustainability. An article was published for RTÉ Brainstorm on the findings of the project and the team were interviewed by RTÉ Raidió na Gaeltachta. Eight journal papers were published in high impact scientific journals and two further papers are currently under review. Academic outputs reached international audiences via the peer-review literature and the existing networks provided by the SFI MaREI centre for energy, climate and marine and IEA Bioenergy.

Note - Both Section 3 and Section 4 of this Final Report are required for SEAI review purposes only and will not be made publicly available.

SECTION 3: COMMUNICATION & DISSEMINATION (max 3 pages)

3.1 Communication, Dissemination and Exploitation

Websites: A webpage for the EcoAD project has been added to the MaREI website.
https://www.marei.ie/project/ecoad/
Twitter: A Twitter account has been created for the project. Please find it at the link below:
https://twitter.com/EcoADIreland
The EcoAD team published an article on **RTÉ Brainstorm** Could anaerobic digestion reduce emissions and natural gas use? (rte.ie)
The EcoAD team have been interviewed on **RTÉ Raidió na Gaeltachta** (https://soundcloud.com/nuacht-an-deiscirt/donal-o-ceileachair?utm_source=clipboard&utm_medium=text&utm_campaign=social_sharing).
The EcoAD team presented at the Anaerobic Digestion Webinar hosted by the **Dingle Hub**:
https://www.youtube.com/watch?v=SsrayMbsE7Y

Conferences See Table 3.2
IEA Bioenergy Task 37: Prof Murphy led Task 37 "Energy from biogas" of IEA Bioenergy from 2016 to 2021. Dr Wall is the alternate Ireland delegate.

- Jerry D Murphy (January 21, 2021) "Integration of biogas systems into the energy system; Power to X: the role of electricity in fuel production" International Energy Agency Bioenergy webinar
- Jerry D Murphy and David Wall (November 22, 2021) "Renewable Gas: Discussion on the state of the industry and its future in a decarbonised world" Invited keynote at Bioenergy Australia Conference
- Jerry D Murphy (December 2, 2021) "State of the art in Green Gas" Invited keynote International Energy Agency Bioenergy Conference "Bioenergy: A critical path to carbon neutrality"

Three IEA Bioenergy reports were published with authorship from the EcoAD group (Dr O'Shea, Dr. Wall and Prof. Murphy):

1. Potential and utilization of manure to generate biogas in seven countries;
2. Perspectives on biomethane as a transport fuel within a circular economy, energy, and environmental system;
3. Renewable Gas – discussion on the state of the industry and its future in a decarbonised world;
4. The role of biogas and biomethane in pathway to net zero;

Other dissemination activities undertaken in the reporting year included for:

- Jerry D Murphy (January 23, 2021) "Power to X: the role of electricity in fuel production" Invited Keynote presentation to State International Center for BioEnergy Science and Technology, Ministry of Science and Technology (*i*BEST), China
- Jerry D Murphy (March 2, 2021) "Biogas solutions for sustainable development – international outlook" Invited Keynote presentation at Goldrushen Conference, Sweden
- Jerry D Murphy (March 9, 2021) "Advanced fuels in circular economy" Presentation to IDA
- Jerry D Murphy (March 17, 2021) "Overview of MaREI Centre and IEA Bioenergy work" Presentation to Johnson and Johnson.
- Jerry D Murphy (May 24th, 2022) Keynote, "Circular Economy, Energy and Environment", Linkoping University, Sweden.

Dissemination Summary Tables

Scientific publications listed in Table 3.1. All dissemination activities listed in Table 3.2.

3.2 Intellectual Property Management & Exploitation

No patents or IP are generated as a result of this research award.

Table 3.1 – List of Scientific Publications

Title	Main Author	Journal Title	Number, Date or Frequency	Publisher	Year of Publication	open access?	Peer-reviewed?
Alternative energy management strategies for large industry in non-gas-grid regions using on-farm biomethane	Dónal Ó Céileachair	Applied Energy	Volume 303, 1 December 2021, 117627	Elsevier	2021	Y	Y
Emerging bioelectrochemical technologies for biogas production and upgrading in cascading circular bioenergy systems	Xue Ning	iScience	Volume 24, Issue 9, 24 September 2021, 102998	CellPress	2021	Y	Y
Assessing the cost variability of emissions abatement in small-scale on-farm anaerobic digestion	Jorge Diaz	DeCarbon	Volume 1, 1000008	Elsevier	2023	Y	Y
A perspective on methodologies and system boundaries to develop abatement cost for on-farm anaerobic digestion	Jorge Diaz	*BioEngineered*	Volume 14, Issue 2, 4 August 2023, 2245991	Taylor & Francis	2023	Y	Y
The effect of seasonal biomass availability and energy demand on the operation of an on-farm biomethane plant	Dónal Ó Céileachair	Journal of Cleaner Production	Volume 368, 25 September 2022, 133129	Elsevier	2023	Y	Y
Logistical considerations and challenges in deploying virtual biomethane pipelines to serve on-farm biogas plants	Dónal Ó Céileachair	Journal of Cleaner Production	Volume 407, 25 June 2023, 137075	Elsevier	2023	Y	Y
Improving the efficiency of anaerobic digestion and optimizing in-situ CO_2 bioconversion through the enhanced local electric field of microbe-electrode interface.	Xue Ning	*Renewable and Sustainable Energy Reviews*	revisions being processed	Elsevier	2023	Y	Y
Biochar facilitates biohydrogen and biomethane production through batch single-stage and two-stage digestion of grass silage and cattle slurry	Xue Ning	*Journal of Cleaner Production*	Volume 426, 30 September 2023, 139155	Elsevier	2023	Y	Y
Improving biomethane production from biochar-supplemented two-stage anaerobic digestion of on-farm feedstocks	Xue Ning	*Journal of Cleaner Production*	Volume 423, 15 October 2023, 138723	Elsevier	2023	Y	Y
Tip-enhanced electric field to facilitate microbe-electrode interaction on the biocathode of microbial CO_2 electrosynthesis	Xue Ning	*Manuscript, ready to submit*	ready to submit				
A methodology for designing biogas pipelines	Dónal Ó Céileachair	*Fuel*	n/a Under Review	Elsevier	2023	Y	Y

Table 3.2 – List of Dissemination Activities

Type of Activity	Main Leader	Title	Date/Period	Location	Audience*	Audience size
Conference Presentation	All phD students	Environ	16-18 June 2021	online	Industry, Policy makers	50
IEA Bioenergy webinar	Jerry Murphy	Integration of biogas systems into the energy system,Power to X: the role of electricity in fuel production	21st January 2021	online	Industry, Policy makers	>100
Bioenergy Australia Conference	David Wall Jerry Murphy	Renewable Gas: Discussion on the state of the industry and its future in a decarbonised world	22nd November 2021	online	Industry, Policy makers, Scientific community	50
IEA Bioenergy Conference	Jerry Murphy	State of the art in Green Gas	2nd December 2021	online	Industry, Policy makers, Scientific community	>100
Presentation	Jerry Murphy	Advanced fuels in circular economy, for IDA	9th March 2021	online	Industry	n/a

Type of Activity	Main Leader	Title	Date/Period	Location	Audience*	Audience size
Presentation	Jerry Murphy	Power to X: the role of electricity in fuel production For State International Center for BioEnergy Science and Technology, Ministry of Science and Technology (*i*BEST), China	23rd January 2021	online	Industry, Policy makers, Scientific community	>50
Presentation	Jerry Murphy	Biogas solutions for sustainable development – international outlook, Goldrushen Conference, Sweden	2nd March 2021	Online	Industry, Policy makers	>50
Presentation(s)	All phD students	Research Progress Updates: 3rd Feb, 19th March, 28th April, 4th May, 8th June, 30th August, 26th October 2021; 24th Jan, 7th February, 21st March, April 8th, 20th June, 19th Dec, 2022	2020-2023	online	Scientific community	15-30
Presentation	David Wall Jerry Murphy	Overview of MaREI Centre and IEA Bioenergy work, for Johnson & Johnson	18th March 2021	online	Industry	n/a
Presentation	Xue Ning	Emerging cascading bio-electrochemical systems for enhanced biogas production, to the Ireland Chinese Association of Environment & Energy	4-5th December 2021	online	Civil Society, Scientific Community	n/a
Presentation	Richen Lin, Jerry Murphy	Cascading Circular Bioenergy Systems, MaREI 8 year site review presentation	21-23 September 2021	UCC (online)	Industry, Policy makers, Academics	250
Panel discussion	Richard O'Shea	Redefining Slurry from Waste to Gold, the National Dairy Show	21 October 2021	Online	Industry, Policy makers, Farmers	n/a
Radio interview	Dónal Ó Céileachair	5 min interview on EcoAD project and AD in general, for special episode during Ploughing Championship	21 September 2022	Radio and Online	General Public	n/a
MaREI Symposium	All phD students	Poster presentations on work carried out during course of EcoAD project	26-27 May 2022	NUIG	Scientific Community	500
Webinar/Workshop	All phD students	Recorded presentations on work carried out during course of EcoAD project, for the Dingle Peninsula	22nd April 2022	Online & Dingle Hub	General Public	
Conference Presentation	Jorge Diaz	Environ Oral Presentation. "'Marginal abatement cost curves for biogas in Ireland: Assessing on-farm anaerobic digestion through the use of an enviro-economic calculation tool"	20 to 22nd June 2022	Ulster University	Scientific community	100
Presentation	Jerry Murphy Richard O'Shea	Overview of the MaREI centre; Circular Economy, Energy and Environmental Systems group; and EcoAD, to University of British Columbia	22nd September 2022	UCC (Online)	Academia	n/a
Workshop	Xue Ning	Ethanol and Acetate production through microbial electrosynthesis in cascading circular bioeconomy systems	29th - 31st March, 2023	Cambridge, UK	Academia	150
Poster Presentation	Xue Ning, Jorge Diaz	4th International Conference for Bioresource Technology microbial CO_2 electrosynthesis; carbon abatement cost of on-farm anaerobic digestion systems (Received best poster award)	14-18 May 2023	Lake Garda, Italy	Academia	1000
Presentation to ESRI	David Wall, Richard O'Shea, Jerry Murphy	Overview of the MaREI centre; Circular Economy, Energy and Environmental Systems group; and EcoAD	14 August 2023	UCC	Scientific community	10
Presentation to Tirlan	David Wall, Richard O'Shea	Overview of the MaREI centre; Circular Economy, Energy and Environmental Systems group; and EcoAD	31 August 2023	UCC	Industry	10
Podcast	Jerry d Murphy	On the pathway towards a net zero future: the role of biogas in the green energy transition https://www.youtube.com/watch?v=KOAZEubuOiw	13 September 2023	Youtube	Broad	127 views
Presentation	Jerry d Murphy	Biomethane Opportunities; Ireland Strategic Investment Fund	4th October, 2023	Kilkenny	Finance, Policy makers, Industry	150

SECTION 4: PROJECT STATUS & WORK PLAN

4.1 Work Plan

Please provide your list of work packages in Table 4.1 below, as detailed in your original Application Form, and include a status update for each.

Table 4.1 – List of Work Packages

No.	Title	Status Update and Completion Status (%)
WP 1	Enhancing on-farm digestion efficiency through novel pretreatments	Experimental work has been completed to evaluate temperature-phased and single-phase anaerobic digestion systems using typical Irish feedstock (grass and cattle slurry) in terms of overall energy yield, process stability and process efficiency. (100%)
WP 2	Integrating electro-methanogenesis with anaerobic digestion to increase biomethane conversion	Experimental work on electron transfer promotion on biomethane conversion from microbial electrolysis cell (MEC) - anaerobic digestion systems was completed. This work investigated the effects of biochar addition, external voltage application, and their combination in lab-scale MEC-AD systems, in parallel with a control digester without electron transfer promotion. Three journal papers have been published with another two further papers currently under review. (100%)
WP 3	Optimising the logistics of on farm anaerobic digestion in Ireland	A literature review was completed within 6 months of the project start date. A paper was developed on alternative energy management strategies for large industry in non-gas-grid regions using on-farm biomethane. This paper was subsequently used to build further analysis and models. The effects of slurry seasonality and gas demand seasonality on the operations of an AD plant were modelled. A model has been developed on optimising a virtual biomethane pipeline and was adapted towards a mobile upgrading and compression unit. A model of biogas pipelines, including for the mapping out of a biogas pipeline network, was developed using optimisation software. Three journal papers have been published with another paper currently under review. (100%)
WP 4	Techno-economic analysis of on-farm anaerobic digestion systems.	A literature review was completed on the existing techno-economic analysis (TEA) of on-farm AD systems. The need for a TEA tool that encompasses both the environmental and financial performance of a system to produce accurate marginal abatement cost curves was proposed. A TEA tool was then developed that integrates both financial and environmental calculations for different configurations of AD systems. The tool was used to calculate the abatement cost and potential of different on-farm AD scenarios. The integration of novel on-farm digestion system was assessed using the TEA tool to compare its performance against a baseline AD system. This has also been extended to evaluate the cost to make on-farm AD competitive based on the logistic costs to deliver biogas. Two journal papers have been published. (100%)
WP 5	Management, communication, and dissemination	A communications plan was established. Various activities have been achieved as part of the communications plan (Twitter page, website, workshop attendance, group meetings, IEA Bioenergy activities). The third and final Annual Technical reports have now been submitted to SEAI. (100%)

In Table 4.2, please include details for each work package (copy and replicate the Table for each work package as required). Please provide an update on the progress, the specific milestones and deliverables achieved, and clearly identify any deviations from the original proposed work packages.

Table 4.2 – Summary of Work Packages

WP No. & Title	**WP1 Enhancing on-farm digestion efficiency through novel pretreatments**		
Start Month No.	1	**Start Month No.**	1
WP Lead	Dr David Wall		
WP Contributors	PhD1, Prof Jerry Murphy, Dr Richen Lin, Dr Richard O'Shea		
Objective(s)	**WP1-O1:** Literature review of hydrothermal hydrolysis and biological acidification	Completion Update: 100%	
	WP1-O2: Develop and optimise biological acidification as a pretreatment method for Irish agricultural feedstock in laboratory systems	Completion Update: 100%	
	WP1-O3: Develop and optimise hydrothermal hydrolysis as a pretreatment method for Irish agricultural feedstock in laboratory systems	Completion Update: 100%	
Description (max 200 words)	Two pretreatment strategies (biological acidification and hydrothermal hydrolysis) will be assessed. For biological acidification, the experiments will be performed under both mesophilic (35°C) and thermophilic (55 °C) temperature using the Automatic Methane Potential Test System (BioProcess Control AMPTS) with 15 × 500 mL fermenters. The effectiveness of biological acidification on typical Irish feedstocks (such as grass and straw) will be evaluated in terms of the production and composition of volatile fatty acids. A temperature phased AD process will then be developed to assess biogas production using batch fermenters. To increase the Technology Readiness Level, the system will be optimised at 5 L continuous scale operation to optimise operational parameters such as organic loading rate and hydraulic retention time. Hydrothermal hydrolysis is considered an effective pretreatment process that can significantly reduce lignocellulose recalcitrance. Hydrothermal pretreatment will be performed using a microwave digestion system (CEM Mars 6). The conditions will be optimised in terms of temperature (100-180 °C), time (5-30 min), and solid loading (5-50%). Solubilisation of feedstock and reducing sugars yield after pretreatment will be analysed. Based on that, a kinetic hydrolysis model can be developed using an irreversible first-order reaction to elucidate the competitive reactions during hydrolysis.		
Milestones	**WP1-M1:** Completion of literature review on pretreatment technologies **WP1-M2:** Completion of batch experiment on biological acidification **WP1-M3:** Completion of batch experiment on hydrothermal hydrolysis **WP1-M4:** Completion of continuous experiment on biological acidification	Completion Status (%):100% Completion Status (%):100%	
Deliverables	**WP1-D1:** Literature review examining the pretreatment technologies. **WP1-D2:** Conference paper on biomass pretreatments for on-farm AD **WP1-D3:** Journal paper manuscript on hydrothermal hydrolysis and biological acidification for improving on-farm AD	Completion Status (%):100% Completion Status (%):100%	
Deviations from planned WP (if applicable)	N/A		
Key Outcomes	• Co-digestion of grass silage and cattle slurry was enhanced due to biochar addition in batch two-stage anaerobic digestion. • Continuous two-stage anaerobic digestion systems performed better than continuous single-stage systems. Addition of biochar improved performance in both continuous single and two-stage anaerobic digestion systems.		

WP No. & Title	**WP2 Integrating electro-methanogenesis with anaerobic digestion to increase biomethane conversion**		
Start Month No.	1	**Start Month No.**	1
WP Lead	Dr Richen Lin		
WP Contributors	PhD1, Dr David Wall, Dr Richard O'Shea, Prof Jerry Murphy		
Objective(s)	**WP2-O1:** Literature review on microbial electron transfer in AD	Completion Update: 100%	
	WP2-O2: Establish direct interspecies electron transfer (DIET) using high-quality hydrochar to promote anaerobic digestion	Completion Update: 100%	
	WP2-O3: Integrate microbial electrolysis cell with anaerobic digestion to facilitate biogas conversion and upgrading	Completion Update: 100%	
Description (max 200 words)	WP2 aims to improve the performance of AD through enhancing the fundamental microbial electron transfer. It is hypothesised that electrically conductive materials could significantly promote DIET and accordingly enhance biomethane production. Firstly, in WP2, the application of conductive materials (high-quality hydrochar) is proposed to radically increase DIET efficiency in methanogenesis. Typical small molecules (such as volatile fatty acids, amino acids, and ethanol) will be assessed as substrates to investigate microbial metabolism in methanogenesis. The maximum electron flux of DIET will be calculated using the Gibbs free energy theory and the Nernst equation. Secondly, a bioelectrochemical system employing Microbial Electrolysis Cell (MEC) will be constructed to improve biogas production efficiency and enable its upgrading to biomethane. The bioelectrochemical system will include cathode (such as stainless steel), anode (such as carbon felt, modified hydrochar material), reference electrode, and DC power supply. The constructed bioelectrochemical system will be inserted into a cylindrical plastic batch reactor (1 L) to form the integrated MEC-AD reactor. The system will be optimised through electrode design, reactor configuration, operation parameters, working voltage, etc. to accelerate feedstock degradation and alter AD microbial community by enriching exoelectrogens and methanogens, thus increasing biogas production and methane concentration.		
Milestones	**WP2-M1:** Completion of literature review on microbial electron transfer in AD **WP2-M2:** Completion of the construction of integrated MEC-AD system **WP2-M3:** Completion of the experiment on DIET enhanced AD with conductive materials **WP2-M4:** Completion of the experiment on enhanced biomethane conversion using MEC-AD system	Completion Status (%):100% Completion Status (%):100%	
Deliverables	**WP2-D1:** Journal paper manuscript on modelling and improving DIET in AD **WP2-D2:** Journal paper manuscript on enhancing biomethane production in an integrated MEC-AD system	Completion Status (%):100% Completion Status (%):100%	
Deviations from planned WP (if applicable)	N/A		
Key Outcomes	• In a future fully decarbonised renewable electricity grid (say 2050 within the EU), all of the bio-electrochemical systems (power to gas, microbial electrolysis cell and microbial electrosynthesis) modelled exhibited positive energy returns when the electricity source would otherwise have been curtailed or constrained. • The optimal system assessed in this work (a microbial electrolysis cell integrated with anaerobic digestion using a modified graphite cathode) enhanced overall biomethane yield by 98% as compared to conventional anaerobic digestion. This as such could reduce the organic feedstock by a factor of 2.		

WP No. & Title	**WP3 Optimising the logistics of on-farm anaerobic digestion in Ireland**	
Start Month No.	1	**Start Month No.** 1
WP Lead	Prof Jerry Murphy	
WP Contributors	PhD2, Dr David Wall, Dr Richen Lin, Dr Richard O'Shea	
Objective(s)	**WP3-O1:** High-level analysis of the range of options for the use of farm-based feedstock for the production of biogas and biomethane.	Completion Update: 100%
	WP3-O2: Development of a model to determine the optimal configuration of multiple on-farm biogas plants providing biogas to a central biogas user via a biogas pipeline.	Completion Update: 100%
	WP3-O3: Development of a model to determine the optimal operation of a system comprising of farm scale anaerobic digesters producing biogas and a mobile upgrading and compression unit.	Completion Update: 100%
Description (max 200 words)	A literature review will be conducted to outline several options for the utilisation of on-farm feedstock for the production of biogas and/or biomethane. Subsequently, a model will be developed to determine the optimal configuration of biogas pipelines to connect a number of farm scale AD plants to a centralised biogas user. This model will be developed following a detailed literature review of gas pipeline hydraulics and modelling of gas network configurations. The model will consider the location and size of the farm scale AD plants, biogas user location, pipeline routes, and associated costs. Software such as; ArcGIS, MATLAB or Microsoft Excel will be used. A second model will be developed to determine the optimal configuration of a system containing a mobile upgrading unit to collect and upgrade biogas from a number of farm scale AD plants. A review of literature regarding; mobile compression and upgrading, routing of road-based resource collection and models to minimise costs shall be conducted. The model will be developed using software such as ArcGIS, MATLAB, Microsoft Excel and optimisation software such as GAMS. This work package will use the results of WP4 and data from the most techno-economically viable farm scale AD systems identified.	
Milestones	**WP3-M1:** Completed literature reviews **WP3-M2:** Full model development for on-farm digestion systems (biogas pipeline). **WP3-M3:** Full model development for on-farm digestion systems (mobile upgrading). **WP3-M4:** Application of developed models to a test region in Ireland.	Completion Status (%):100% Completion Status (%):100%
Deliverables	**WP3-D1:** Literature review on the options for utilisation of on-farm resources for anaerobic digestion. **WP3-D2:** A logistics model to determine the optimal configuration of multiple on-farm biogas plants providing biogas to a central biogas user via a biogas pipeline. **WP3-D3:** A logistics model to determine the optimal operation of a system comprising of farm scale anaerobic digesters producing biogas and a mobile upgrading and compression unit. **WP3-D4:** Journal paper manuscript on logistics modelling to make on-farm digestion cost competitive in Ireland	Completion Status (%):100% Completion Status (%):100%
Deviations from planned WP (if applicable)	N/A	
Key Outcomes	• A substantial quantity of the national on-farm biomass (17%) is located in excess of 15km from the gas grid but within 15km of a large industry energy user • The current on-farm biomethane resource in Ireland equates to 200% of industrial natural gas use • Pasture-based farming systems account for higher emissions (by 11 g CO2-eq MJ-1) in terms of the biomethane produced from on-farm AD systems • Virtual biomethane pipelines may be used for anaerobic digestion in areas with limited gas grid infrastructure access • Mobile biogas upgrading units carry significant logistical challenges and their resultant higher routing emissions can impact the sustainability of the collected biomethane.	

<table>
<tr><td>WP No. & Title</td><td colspan="3">WP4 Techno-economic analysis of on-farm anaerobic digestion systems</td></tr>
<tr><td>Start Month No.</td><td>1</td><td>Start Month No.</td><td>1</td></tr>
<tr><td>WP Lead</td><td colspan="3">Dr Richard O'Shea</td></tr>
<tr><td>WP Contributors</td><td colspan="3">PhD3, Prof Jerry Murphy, Dr Richen Lin, Dr David Wall</td></tr>
<tr><td rowspan="3">Objective(s)</td><td colspan="2">WP4-O1: Develop a tool to assess the techno-economic feasibility of on-farm anaerobic digestion in Ireland.</td><td>Completion Update: 100%</td></tr>
<tr><td colspan="2">WP4-O2: Conduct a techno-economic assessment of on-farm biogas facilities in Ireland to establish key economic parameters/barriers.</td><td>Completion Update: 100%</td></tr>
<tr><td colspan="2">WP4-O3: Assess the economic viability of feedstock pre-treatment, digestate post-treatment, and novel technologies to enhance on-farm digestion process (based on the results of WP1 and WP2.</td><td>Completion Update: 100%</td></tr>
<tr><td>Description
(max 200 words)</td><td colspan="3">A detailed literature review will be conducted initially to ensure that the baseline technoeconomic assessment (TEA) results for farm scale AD in Ireland is as up to date and relevant as possible. To assess the techno-economic performance of on-farm digestion for a range of scales and feedstock mixes, a TEA tool will be developed. The tool will be based on best practices in terms of assessing techno-economic performance based on a detailed literature review and assessment of similar existing tools such as the System Adviser Model developed by NREL. The use of specific software such as SuperPro Designer will also influence the development of the tool. The TEA tool will calculate technical performance indicators e.g. efficiency and energy production, and typical economic parameters such as; NPV, IRR, net payback period and LCOE (cost per unit of energy produced). The tool will be capable of conducting a sensitivity analysis on selected technical and economic variables to highlight the parameters which have the greatest impact on the financial viability of on-farm AD facilities for both "standard" and "novel" systems. Baseline on-farm AD will be defined and evaluated against opportunities for further development.</td></tr>
<tr><td>Milestones</td><td colspan="2">WP4-M1: Completion of literature reviews
WP4-M2: Developed TEA tool to assess on farm anaerobic digestion facilities.
WP4-M3: Use of TEA tool to determine performance of baseline on-farm AD in Ireland.
WP4-M4: Use of TEA tool to determine the performance on novel pre-treatment and AD technologies applied to on-farm AD in Ireland.</td><td>Completion Status (%):100%
Completion Status (%):100%</td></tr>
<tr><td>Deliverables</td><td colspan="2">WP4-D1: Literature review of TEA methods and prior applications to anaerobic digestion.
WP4-D2: TEA evaluation tool complete with methodology.
WP4-D3: Economic assessment of baseline and novel on-farm digestion systems using TEA tool.
WP4-D4: Journal paper manuscript on TEA of on-farm digestion technologies in Ireland.</td><td>Completion Status (%):100%
Completion Status (%):100%</td></tr>
<tr><td>Deviations from planned WP
(if applicable)</td><td colspan="3">N/a</td></tr>
<tr><td>Key Outcomes</td><td colspan="3">• The abatement cost of AD systems varies based on the different processes considered within the system boundary
• On-farm anaerobic digestion abatement costs ranged from -117 to +79 €/tCO₂eq for small scale systems.
• Biogas for the production of electricity and heat in a CHP unit had a higher probability of achieving lower abatement costs
• To make biogas upgrading financially viable at small scale, additional incentives and revenue streams are required, along with the integration of a CHP unit to meet the parasitic energy demand of the system.</td></tr>
</table>

WP No. & Title	**WP5 Management, communication and dissemination**	
Start Month No.	1	**Start Month No.** 1
WP Lead	Prof Jerry Murphy	
WP Contributors	PhD1, PhD2, PhD3, Dr Richard O'Shea, Dr Richen Lin, Dr David Wall	
Objective(s)	**WP5-O1:** EcoAD project management	Completion Update: 100%
	WP5-O2: EcoAD project communicaton	Completion Update: 100%
	WP5-O3: EcoAD project dissemination	Completion Update: 100%
Description (max 200 words)	Prof Jerry Murphy will coordinate all project work (including technical direction, progress monitoring, budgeting, reporting, dissemination and other management duties) and liaise with SEAI. The WP leaders will organise monthly meetings with the PhD students and project team to ensure milestones and deliverables are on target. Annual technical and financial reports will be submitted to SEAI. A Communication and Dissemination plan will be established at the outset of the project and updated as the project progresses (see Section 3.3). The plan will include for various activities as part of MaREI's Education and Public Engagement (EPE) program, promoting the research to researchers, school/university students, Irish farmers, the biogas industry and the general public. The EcoAD project will also include for workshops, conference presentations, public science events, community engagement, webinars, website and social media management to enhance the communication and dissemination for an on-farm AD industry in Ireland. The IEA Bioenergy Task 37 workshops will be targeted to provide key information to academic/industrial stakeholders at an international level. To disseminate the research output to academia, it is expected that at least six peer reviewed journal papers on the topics of feedstock pretreatment, electro-methanogenesis, techno-economic analysis will be published from the EcoAD project.	
Milestones	**WP5-M1:** Completion of a communication and dissemination plan **WP5-M2**: Completion of annual reports and final report **WP5-M3:** Organisation of annual progress workshops and final stakeholder workshop	Completion Status (%):100% Completion Status (%):100%
Deliverables	**WP5-D1:** A communication and dissemination plan **WP5-D2:** Annual reports and final report	Completion Status (%):100% Completion Status (%):100%
Deviations from planned WP (if applicable)	N/a	
Key Outcomes	• A communication and dissemination plan was successfully developed and implemented. • Annual reports and final reports were submitted.	

ANNEX 1 – CASE STUDY TEMPLATE

Please complete the SEAI Case Study Template below. The details below may be used for SEAI promotional activities, e.g. project dissemination on SEAI Website or SEAI Twitter account.

Project Title	
Developing Economic Solutions for on-farm Anaerobic Digestion technologies under Irish conditions (EcoAD)	
Project Summary – Please provide a brief and high-level summary of your project. (Max 3 sentences)	
The EcoAD project explores economic solutions for small-scale, on-farm anaerobic digestion technologies using typical farm feedstock (slurries, grass). Finding the most efficient and cost-effective biogas and biomethane production scenarios is of relevance to reducing emissions from the agricultural sector in Ireland. The project assessed three key aspects in relation to small-scale on-farm AD in Ireland: Logistics, Technology and Economics.	
What challenges did you face? Challenges can be technical (e.g. sensor failure), managerial (e.g. delay in the hiring process), financial (e.g. unexpected costs), etc.	
Due to the Covid-19 pandemic, the project team were constrained to remote working for a number of months at the beginning of the project. As a result, the project timelines had to be amended to start laboratory work at a later stage than originally planned.	
Three key statistics – If applicable, please provide three key statistics related to your RD&D Project: e.g. X kW generation capacity; X Papers Published; X Communities/Users involved; X potential energy/cost savings	
1.	11 journal papers in top international press developed from the project work (8 published, 3 currently under review). In particular we have added to the scientific knowledge base of improved multi-phase digestion, through addition of biochar and electrodes.
2.	3 PhD students have obtained substantial skills and knowledge which can benefit the AD industry in Ireland. One of our PhD graduates is now working with the Ireland Strategic Investment fund (Irish wealth fund) and is tasked with pathways that will provide the 2030 target of 5.7 TWh of biomethane, Another of our PhD graduates will take up a position with Teagasc in November.
3.	We have shared our learnings through c. 23 dissemination events, including podcasts, invited talks and conference presentations.
What would you regard as the three most significant achievements or impacts enabled by this SEAI funding?	
1.	Generating a more accurate range of abatement costs for small-scale, on-farm anaerobic digestion in Ireland
2.	Progressing the technology readiness level of novel anaerobic digestion technologies such as the microbial electrolysis cell (MEC) which can increase biomethane production per unit of feedstock and reduce the quantity of feedstock required
3.	Improved understanding of the logistics of anaerobic digestion in Ireland in terms of feedstock resource, location and seasonality, the potential to offset natural gas use in industry through biomethane, and the delivery of energy to the end user in decentralised regions.
Other	
How has this or will this research project be of benefit to Ireland?	
A 25% reduction in greenhouse gas emissions from the Irish agricultural sector is required by 2030. Anaerobic digestion is proposed as one measure to assist in achieving this target. The Climate Action Plan has a target of 5.7TWh of biomethane by 2030. Whilst the industry in Ireland is nascent,	

factors such as the logistics of feedstock and energy delivery, future technologies of most potential and the economic viability of such systems need to be further investigated. Ireland has a large quantity of agricultural biomass such as grass and livestock slurry that can potentially be used for anaerobic digestion on Irish farms. The EcoAD project provides much needed information on delivering future best practices with regards to the economic viability of on-farm biogas and biomethane production systems. This analysis can inform policy makers and stakeholders on the optimal pathways for deployment of small-scale anaerobic digestion systems that are farm based and can thus inform policy direction in terms of meeting Ireland's decarbonisation objectives.
What was the biggest learning outcome throughout the project?
Some of the key learning outcomes of the EcoAD project were: • A substantial quantity of the national on-farm biomass (17%) is located in excess of 15km from the gas grid but within 15km of a large industry energy user. • The current on-farm biomethane resource in Ireland equates to 200% of industrial natural gas use. • Pasture-based farming systems may increase the production related GHG emissions of biomethane by 11 g CO_2-eq MJ^{-1}. • Virtual biomethane pipelines may be used to link anaerobic digesters to energy end users in areas with limited gas grid infrastructure. • Mobile biogas upgrading units present logistical challenges and their higher transport related emissions can impact the sustainability of the biomethane. • Biochar addition enhances hydrolysis and acidification and methane production in the digestion process. • The increased biomethane output from the microbial electrolysis cell (MEC) anaerobic digestion system include a 6-fold increase in energy output in the form of biomethane as compared to the electrical energy input to the system in the form of a 1V current. • The abatement cost of AD systems vary based on the different processes considered within the system boundary, • On-farm anaerobic digestion abatement costs ranged from -117 to +79 €/tCO_2eq for small scale systems. • Biogas for the production of electricity and heat in a CHP unit had a higher probability of achieving lower abatement costs. • To make biogas upgrading financially viable at small scale, additional incentives and revenue streams are required along with the integration of a CHP unit to meet the parasitic energy demand of the system.
What has this SEAI funding enabled for you/your organisation? (e.g. building capacity, developing a product, opening new markets, growth in revenue). Please be specific and quantify your responses where possible.
The generous funding from SEAI and Gas Networks Ireland enabled laboratory scale prototypes of novel anaerobic digestion technologies to be developed. Furthermore, it allowed for collaboration and feedback from key stakeholders in the industry (Department of Agriculture, Teagasc, GNI, SEAI, Dingel Hub) to lead data-informed approaches to future decision making regarding on-farm biogas production in Ireland.
What advice would you give to other researchers?
Enjoy the science and maximise opportunities to disseminate the findings. You must find an interesting narrative that you can communicate in a fashion that is understandable, that highlights the importance of your work and creates interest in society. Working with communities in a co-design model can maximise the opportunity for commercialisation of your research.
If you wish, please describe your overall experience working on this project (e.g. are you happy with its success, what was the highlight for you, and/or what do you have planned next)
This project has been a great success. Our Supervisory team led by David Wall lent its support across all work packages. Our PhD team worked very well together and displayed differing but complimentary skill sets. Dr Xue Ning brought lab excellence to our novel systems. Dr Donal O' Ceileachair excelled in logistics design and Jorge Huerta brought these technologies together

through the lens of marginal abatement costs. This work has led to two more SEAI funded projects; CABBBIE examining small scale microalgal biorefineries, and ShipFUEL-IE looking at production of methanol for shipping.

Please submit *a separate e-copy of any* ***pictures / maps / images / graphics*** *inserted into the text above, as individual .jpeg, .tiff, .csv files to ensure good quality printing.*
Please also submit 3 ***research project cover pictures*** *(e.g., team photo, site photos, prototype photos, research lab photos etc). Please ensure the below picture requirements are met:*

- *Pictures must be of high quality to ensure good quality printing*
- *Layout: Landscape*
- *Format: Jpeg*
- *Size: Minimum 1200 x 1200 pixels*

ANNEX 2 – PROJECT COMPLETION SURVEY

Workforce Statistics *Please indicate in the table below the number of people who worked on this project within the Lead/Partner Organisation Types listed*		
Project Staff (By Lead/Partner Organisation Type)	**Number of Women**	**Number of Men**
Industry and SMEs (if applicable)	N/A	N/A
Academia or publicly funded research institutes (if applicable)	1	6
Of which, number of PhD Students	1	2
Other Public Sector or Semi-state Organisations (if applicable)	N/A	N/A
How many of the above staff were recruited specifically for this project?	1	2

Engagement – Civil Society and Policy Makers	
Did your project involve working with students and/or school pupils (e.g. open days, participation in science)?	
Yes – Please specify	Yes
No	
Did your project engage with societal actors beyond the research or industrial community?	
Yes – Please specify	Yes, Teagasc
No	
If yes, did you engage with citizens or organised societal groups (select from the below options)?	
No	
Yes – in determining the research to perform	Dingle Hub
Yes – while implementing the research	
Yes – in communication/dissemination of research results	
Did you engage with government / public bodies or policy makers (including international organisations)?	
No	
Yes – in framing the research	DAFM
Yes – while implementing the research	
Yes – in communication/dissemination of research results	
If you marked yes above and engaged with international organisations, please specify which organisation and which country here:	
Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?	
Yes – as a primary objective	Yes
Yes – as a secondary objective	
No	
If you marked yes above, please add details here	
If yes, at which level?	
Local / Regional Level	
National Level	Yes
European Level	
International Level	

Dissemination and Market Readiness	
How many articles were published/accepted for publication in peer-reviewed journals?	8
How many articles were presented and published in conference proceedings?	
How many new patent applications have been made?	0
How many spin-off companies were created/ are planned as a direct result of this project?. If you marked "are planned", please give an estimation of the date of creation.	
Did the project result in a market ready solution (e.g. a product, a service)? (Yes/No)	No

Communication Statistics	
Which of the following have been used to communicate information about your project? (tick as appropriate)	
☑ Press Release ☑ Communication via social media (Twitter, Linkedin, Applicant website, etc.) ☑ Media Briefing ☑TV coverage / report ☑ Radio coverage / report ☑ Brochures / posters / flyers □ DVD / Film / Multimedia □ Other (please specify):	□ Coverage in specialist press □ Coverage in general press □ Coverage in national press □ Coverage in international press □ Website for the general public ☑ Event targeting general public (Festival, conference, exhibition) ☑ Scientific conferences □ Other (please specify):

SEAI National Energy RD&D Funding Programme - Feedback
If you have any feedback or suggestions in relation to the SEAI National Energy RD&D Funding Programme, please provide below: