End of Project Report

Project Name: **Enhancement of the Anaerobic Digestion Process for Biomethane Production**		
Company: **HydroStar Europe Ltd.**	START DATE: **01/01/2025**	END DATE: **29/05/2026**

Executive Summary

Biomethane is currently the most mature low-carbon gas available for direct injection into gas distribution networks and already plays an important role within the Wales & West Utilities (WWU) network. However, conventional anaerobic digestion typically produces biogas with a relatively low methane content, increasing the need for gas upgrading and, in some cases, propane enrichment to meet network-entry requirements. These processes add cost, complexity and emissions to biomethane production.

This project investigated whether controlled hydrogen injection into the anaerobic digestion process could increase methane production at source by converting a greater proportion of the carbon dioxide in the biogas into methane through existing biological processes. Increasing the methane content within the digester could reduce the amount of carbon dioxide that must be removed during downstream upgrading. Laboratory experiments undertaken at the University of Southampton tested the process under controlled biological conditions. The results showed that hydrogen-assisted biomethanisation could be achieved without destabilising the anaerobic digestion process, provided that hydrogen dosing was introduced gradually and key operating conditions were monitored. Hydrogen injection delivered a clear and sustained uplift in biomethane production across both maize- and wheat-fed digesters. Biomethane concentrations increased from 54% at baseline to 82–83% under hydrogen-assisted operation, with methane yield rising by 55% relative to the control digesters. This work reduced biological uncertainty and informed the design of the on-site testing.

Building on the laboratory results, a small-scale demonstrator was operated within a commercial anaerobic digestion facility. This tested the process using representative digestate and operating conditions while remaining separate from the main commercial digester. During the trials, methane concentration in the biogas increased from a baseline of around 55% to peaks between 64% and 76% as the hydrogen injection rate increased from 0.25 to 0.75 L/min during four-hour dosing periods.

A network-level assessment applied these scenarios across all 22 biomethane plants connected to the WWU network. The assessment indicated that annual renewable gas delivery could increase from the current baseline of 1,870 GWh in the 2025/2026 regulatory year to between 2,311 GWh and 2,790 GWh if similar performance could be achieved and maintained across the network.

The Demonstrator 0.50 scenario is used as the near-term planning case because it produced a greater methane increase than the 0.25 L/min scenario while using hydrogen more efficiently and presenting fewer pH management concerns than the 0.75 L/min scenario. Under this scenario, annual renewable gas delivery would increase to approximately 2,472 GWh, representing a 32.2% increase. The number of equivalent households supplied would increase from 163,000 to approximately 215,500.

The environmental assessment found that a modelled 50% increase in output from a typical 1,000 scmh plant could theoretically save approximately 4,167 tonnes of carbon dioxide equivalent emissions per year, assuming complete hydrogen conversion. Lower hydrogen conversion efficiencies would increase the amount of hydrogen required and reduce the carbon saving. The economic assessment found that the same increase in output could avoid approximately £4 million to £7.5 million of the cost of building equivalent new capacity. Financial viability depends on plant costs, gas value, hydrogen price and operating conditions and should therefore be assessed for each plant individually.

From a network perspective, the project demonstrates that hydrogen-assisted anaerobic digestion is technically possible and could provide biomethane producers with another option for increasing renewable gas production from existing infrastructure. Hydrogen-assisted biomethanisation increases the methane content of the biogas leaving the digester, meaning the raw gas enters the upgrading system with a higher calorific value and a lower CO_2 fraction than conventional AD. This provides a higher-quality feed gas for the scrubbing system, which still removes impurities as normal. As the methane fraction is higher, the upgraded biomethane would, in principle, require less propane to meet CV specifications, although the exact impact depends on the

upgrading technology, site-specific CV targets, and any blending strategies used by the producer. In cases where total biogas flow increases as a result of hydrogen-assisted operation, the absolute propane requirement could rise even if the per-unit CV uplift reduces the proportional need for enrichment.

The main remaining uncertainty is the difference between the sustained methane concentrations achieved in the laboratory and the short-term peaks observed during the on-site trials, together with the hydrogen conversion efficiency that can be achieved during continuous commercial operation. Overall, the project provides WWU with evidence that biomethane producers may be able to use this approach in the future while continuing to meet all applicable network-entry requirements. The recommended next step is an extended commercial-scale demonstration using continuous operation over several months.

1. Introduction

GDNs play a critical role in enabling sustainable and affordable energy solutions for customers while maintaining the safe and reliable operation of existing gas infrastructure. For networks such as WWU, particular value is placed on low-carbon gases that are compatible with existing network specifications and operational practices, as these can support emissions reduction without requiring fundamental changes to network assets. Biomethane is currently the most established low-carbon gas compatible with the gas distribution network and is already injected across the UK, including within the WWU network. It contributes to both decarbonisation objectives and security of supply by providing a domestically produced, renewable gas that can be delivered through existing infrastructure.

Biogas produced by the AD process contains a mixture of gases, with the main components being methane (CH_4), carbon dioxide (CO_2), hydrogen sulphide (H_2S) and water vapour. Methane is the component retained when raw biogas is upgraded to produce biomethane for network injection. Raw biogas from conventional AD systems often contains around 50% methane, with the remaining gas largely comprising carbon dioxide and other impurities. For biomethane to be injected into a gas distribution network, it must comply with defined network entry requirements under the Gas Safety (Management) Regulations (GSMR), including limits on impurity concentrations and a minimum calorific value consistent with natural gas specifications. As a consequence of the relatively low methane concentration in raw biogas, carbon dioxide and other impurity gases must be removed prior to injection, typically through gas scrubbing processes. In addition, the resulting biomethane often has a calorific value below network requirements, necessitating the addition of propane to raise the calorific value to compliant levels. Both gas scrubbing and propane addition introduce capital and operational costs and represent a key technical and economic constraint on the wider deployment of biomethane. Furthermore, while anaerobic digestion is a renewable energy technology, the carbon dioxide present in the biogas stream is not utilised in a productive manner, unlike biomethane which can be used directly for heat or power.

The purpose of this project is to investigate whether the anaerobic digestion process can be enhanced through the controlled injection of hydrogen in order to increase biomethane yield. The proposed approach targets the later stages of the AD process, where digestion intermediates and carbon dioxide are converted to methane, by increasing the availability of hydrogen for biological methane formation. By providing a hydrogen-rich environment in controlled quantities and at defined points within the digestion process, the project seeks to increase the proportion of carbon dioxide converted to biomethane through existing biological pathways. This has the effect of shifting the typical approximate 50:50 split between biomethane and carbon dioxide in raw biogas in favour of biomethane. The position of hydrogen injection within the anaerobic digestion process, and its relationship to downstream biomethane formation, is illustrated in Figure 1.

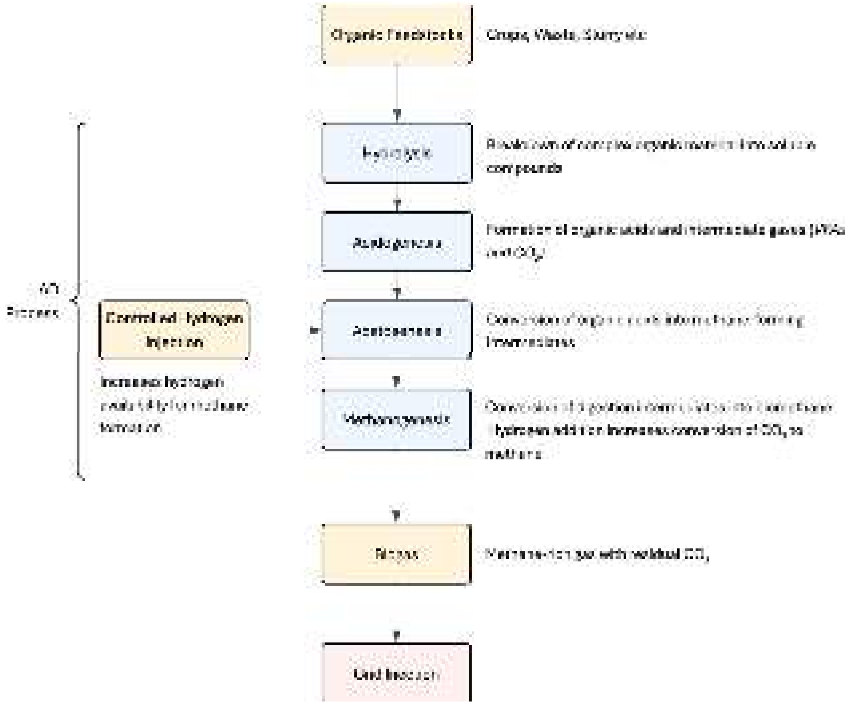

Figure 1: Simplified anaerobic digestion process showing hydrogen-assisted in-situ biomethanisation

Increasing in-situ biomethane production has the potential to deliver benefits that are directly relevant to WWU and other gas distribution networks. Higher methane content at source reduces the burden on downstream gas conditioning processes, providing a higher-quality feed gas for upgrading. This improves the overall efficiency and environmental performance of biomethane supplied to the network, while potentially also reducing operating costs for producers. Because biomethane is already compatible with existing gas infrastructure, any successful optimisation approach could, in principle, be applied to both existing and future AD assets without requiring fundamental changes to the gas network.

An additional system-level benefit of the approach investigated within this project is the provision of an end-use case for green hydrogen. At present, hydrogen cannot be widely blended into gas distribution networks due to regulatory constraints. Using hydrogen to optimise anaerobic digestion provides an alternative route for early hydrogen deployment, while indirectly supporting network decarbonisation and encouraging investment in green hydrogen production ahead of future regulatory change.

The project builds on existing academic literature which identifies the potential for hydrogen injection to increase biomethane yields substantially above 50%, while also highlighting important operational considerations, including the need to manage process acidity and avoid destabilisation of the microbial environment at elevated hydrogen concentrations. These considerations underpin the research-led approach adopted within the project.

HydroStar Europe Ltd leads the project in collaboration with Wales & West Utilities (WWU), an operational AD facility, and the University of Southampton. HydroStar provides expertise in green hydrogen production, handling and downstream applications, together with optimisation modelling for integrated multi-vector energy systems. WWU contributes strategic insight into the role of upgraded biogas within future network operations, reflecting its wider interest in expanding low-carbon gas supply options. The University of Southampton provides specialist anaerobic digestion research capability, while the operational partner supplies the commercial AD context needed to assess practical deployment and performance under real-world conditions.

The project is structured as a research, development and demonstration activity. It comprises a review of current academic and industrial evidence, simulation modelling to assess technical feasibility and identify the operating conditions under which hydrogen injection can be delivered reliably, laboratory-scale testing to validate biological behaviour under controlled conditions, and a small-scale on-site demonstration using a contained test system at an operational AD facility. The on-site demonstration is designed to prove the concept without direct integration with the main digester, thereby avoiding risk to core plant operations.

For WWU, the project is intended to generate practical learning on how biomethane production could be made more efficient, resilient and lower in carbon intensity, informing future network planning and operational strategy. Given that over 700 biogas plants are currently operational across the UK, with a further significant pipeline of projects in development, the learning generated has relevance across multiple gas distribution networks.

2. Simulation Modelling

Simulation modelling was included in this project to establish theoretical operating boundaries for hydrogen injection into the AD process and to inform the design of subsequent experimental work. Given the biological complexity of anaerobic digestion and the potential risks associated with introducing hydrogen into an operational system, modelling was used as an initial, low-risk tool to assess feasibility, identify limiting conditions, and define safe and realistic operating envelopes prior to laboratory and on-site testing.

The simulation modelling was carried out using a spreadsheet-based equilibrium model that calculates gas composition and partial pressures for the CO_2 biomethanisation process under different operating conditions. The approach assumes a closed system with defined gas inputs and reaction completion according to thermodynamic equilibrium. Two modelling scenarios were explored:

- Scenario 1 - Feedstock-based: using representative data for several common AD feedstocks, providing indicative conditions for new or theoretical plants.
- Scenario 2 - Existing digester operation: based on measured operational parameters from current AD systems, providing more reliable and site-specific results.

The model outputs include the predicted equilibrium concentrations of biomethane, carbon dioxide and hydrogen, as well as the corresponding partial pressures. Particular focus was placed on identifying the upper biomethane partial pressure that could be achieved without residual hydrogen in the biogas.

2.1 Simulation Model Inputs

The thermodynamic simulation model incorporates two distinct input frameworks, reflecting different practical applications of hydrogen-enhanced anaerobic digestion. These correspond to Scenario 1 which is based on feedstock and feedstock mix, and Scenario 2, which is based on baseline pH and CO_2 parameters.

Scenario 1: Feedstock-Based Simulation - This scenario estimates hydrogen injection performance based on the properties and proportions of selected feedstocks. It is suited to new or conceptual digesters where feedstock composition is defined but detailed operational data are unavailable.

Key inputs include:

- Temperature: 37 °C (mesophilic conditions)
- Baseline pH: 7.5
- Feedstock composition: for example, 100 % maize, 100 % sewage sludge, or mixed feedstocks such as 50 % slurry / 50 % maize.
- Current daily biogas production: 1000 STP m^3 day^{-1}
- Exogenous CO_2 availability: variable, typically between 0 and 500 STP m^3 day^{-1}
- Baseline biomethane content: 0.55–0.65 (CH_4 fraction of the biogas)
- Specific biomethane production: 0.26–0.35 STP m^3 kg^{-1} VS

These values are derived from the model's feedstock database, which defines typical biomethane yields and volatile solids content for standard AD substrates such as maize, slurry, and sewage sludge.

Scenario 2: Operational Parameter-Based Simulation - The second scenario uses operational parameters which include digester temperature, baseline pH, baseline carbon dioxide partial pressure, and the daily biogas production rate.

Key inputs include:

- Temperature: 37 °C
- Baseline pH: 7.5
- Baseline CO_2 partial pressure: 0.40
- Current daily biogas production: 1000 STP m^3 day^{-1}
- Exogenous CO_2 available: 100 STP m^3 day^{-1}

In both scenarios, the model assumes equilibrium conditions for the reaction $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$, at slightly above atmospheric pressure. Kinetic effects, microbial population dynamics, and gas-liquid mass transfer are not included, ensuring that the results represent the thermodynamic upper limits for biomethane formation under the specified conditions.

However Scenario 2 is considered more reliable because feedstocks in commercial AD plants exhibit substantial variability in composition, moisture content, and biodegradability, even within a single category such as food waste, maize, or slurry. In addition, feedstocks typically remain in the digester for extended retention periods and are often processed in mixed batches. As a result, the gas produced at any given time represents the degradation of material introduced over a longer duration rather than the current feed input.

2.2 Simulation Model Outputs

The simulation provides gas-phase composition data under varying hydrogen injection levels. The principal output is the relationship between biomethane and carbon dioxide partial pressures, identifying the upper threshold of biomethane production at which no unreacted hydrogen remains. At this threshold, biomethane partial pressure is determined by the available carbon dioxide, and further hydrogen addition beyond this point would not increase biomethane yield. Operating below this limit ensures that all hydrogen is converted, and the process remains stable.

2.3 Simulation Model Analysis

The simulation results define the theoretical equilibrium boundary for biomethane enhancement through hydrogen injection. Biomethane partial pressure provides a clear measure of the system's upper limit, while the ratio of hydrogen to carbon dioxide determines how close the process approaches this limit. At typical operating pressures slightly above atmospheric, hydrogen injection does not cause excessive biomethane partial pressures or instability. The model confirms that biomethane production remains within safe and predictable limits at these conditions. Operating below the threshold methane partial pressure allows efficient hydrogen utilisation and avoids the accumulation of residual hydrogen in the product gas. In practical terms, these operating limits correspond to the hydrogen dosing rates and CO_2 availability ranges within which operators can maintain stable digester performance without affecting gas quality or biological activity. By supporting higher in-situ biomethane production, this approach has the potential to reduce the burden on upgrading systems and improve the calorific value consistency of biomethane entering the network.

The model highlights that pH plays a central role in determining the extent of in-situ biomethanisation. Accurate pH monitoring is essential, as pH directly influences the solubility of carbon dioxide and the activity of hydrogenotrophic methanogens. Although the model defines an upper limit based on the available carbon dioxide, this does not restrict overall conversion potential. An external carbon dioxide source could be introduced to enable further hydrogen conversion while remaining within safe equilibrium boundaries.

Feedstock variability introduces significant uncertainty when estimating absolute limits. Scenario 1, which relies on broad feedstock categories, provides generalised data that may not capture real-world variation. Scenario 2, based on operational digester data, is considered more reliable because it reflects actual system behaviour and known parameters such as pH, gas composition, and flow rates.

Feedstock nitrogen content also has an important influence on process performance. High-nitrogen materials, such as poultry manure, typically have elevated baseline pH values. During CO_2 biomethanisation, the reduction of CO_2 to CH_4 decreases the amount of dissolved carbonic acid in the liquid phase, which can further raise pH. Excessive pH may inhibit methanogenic microorganisms and reduce process stability. For this reason, high-nitrogen feedstocks have not been the focus of in-situ CO_2 biomethanisation trials to date. However, as techniques for digestate valorisation and ammonium recovery continue to develop, these feedstocks may become more suitable for hydrogen-assisted digestion in future applications.

It is also recognised that the model cannot represent reaction kinetics or biological adaptation. In practice, hydrogen injection requires an enrichment period for microbial populations capable of utilising hydrogen and carbon dioxide efficiently. Hydrogen's low solubility further limits mass transfer, meaning that effective mixing and the use of small gas bubbles will be necessary to reach the conditions predicted by the model.

2.4 Simulation Model Conclusions

In this context, the biomethane partial pressure threshold represents the equilibrium point at which all available carbon dioxide has been converted to biomethane and no residual hydrogen remains. The threshold is directly determined by the initial CO_2 concentration in the biogas: once this CO_2 is fully consumed, further hydrogen injection produces no additional biomethane. In practice, the starting CO_2 level is measurable in any AD system using standard gas-composition monitoring, allowing operators to estimate how close they are to this thermodynamic limit. Based on the simulation and subsequent analysis, optimal conditions for hydrogen injection can be defined as those that remain below the biomethane partial pressure threshold determined by the model. Within this range:

- Hydrogen is efficiently utilised, with no significant residual gas in the biogas output.
- The system remains stable with respect to pressure and composition.
- pH remains within a biologically acceptable range, preventing inhibition of methanogenic activity.

Maintaining equilibrium between the thermodynamic limit and biological capacity is critical. Operationally, this means gradual hydrogen introduction and close monitoring of pH and volatile fatty acids to prevent intermediate accumulation.

The simulation model originally developed in Excel has been converted into an interactive dashboard using Python. This interface allows users to input custom parameters, after which the system performs the same calculations as the original model to generate corresponding outputs. The dashboard (accessible via - https://ad-simulation-model.streamlit.app/) provides a user-friendly environment for real-time adjustment of process variables and visualisation of biogas production dynamics, supporting both experimental optimisation and operational decision-making.

The simulation work completed in this stage provides a foundation for the next phase of the project, where the modelled hydrogen-injection thresholds will be tested under operating conditions. By defining the biomethane partial pressure limit at which hydrogen is fully consumed, and by mapping how pH, CO_2 availability, and baseline digester conditions influence equilibrium, the model establishes the safe and efficient operating window in which the upcoming demonstrator trials can be conducted.

This model is important because it shows that, under typical digester pressures and carbon dioxide levels, hydrogen injection could increase the proportion of biomethane in the biogas without risking instability, provided dosing stays within the identified limits. Although the actual performance in real digesters will depend on reaction rates, mixing efficiency and microbial behaviour, the thermodynamic model confirms that there is no chemical barrier preventing a high level of CO_2 conversion. The thermodynamic thresholds defined through this modelling informed the design of the subsequent laboratory and demonstrator testing phases.

3. Laboratory Evaluation of Hydrogen Injection

Laboratory-based experimental work was undertaken at the University of Southampton to validate the findings of the simulation modelling under controlled biological conditions and to assess hydrogen-assisted biomethanisation in AD systems. The simulation model defined theoretical operating limits based on thermodynamic equilibrium and the laboratory experiments were used to evaluate the microbial response, process stability, and the interaction between hydrogen injection, pH, and volatile fatty acid (VFA) concentrations.

3.1 Experimental Design and Methodology

Laboratory experiments were conducted using four anaerobic digesters of continuous stirred tank reactor (CSTR) design, the set up can be seen in Figure 2. Each digester comprised a 5 L high-density polyethylene (HDPE) reactor with a working volume of 3 L. Inoculum was sourced from the anaerobic digestion facility, sieved to remove large particles, and distributed evenly across all digesters to ensure consistent initial conditions. The laboratory setup was designed as a controlled mimic of a full-scale anaerobic digester, reproducing key features such as mesophilic temperature, continuous mixing and stable loading conditions, while recognising that commercial digesters typically operate at higher organic loading rates, shorter retention times and with larger-scale, less uniform mixing systems.

Mixing was provided by mechanical stirrers connected via shafts passing through gas-tight draft tubes to 12 V DC motors operating at approximately 100 rpm. Digester temperature was maintained under mesophilic conditions (37 °C) using thermostatically controlled water baths. All digesters were operated at an organic loading rate of 1 g volatile solids (VS) L^{-1} day^{-1} and a hydraulic retention time of 100 days, which represents the average time that material remains in the digester for biological conversion. Biogas production rate and gas composition were monitored daily. Additional process parameters, including pH, total ammoniacal nitrogen

(TAN), total solids, volatile solids, and VFAs, were measured once or twice per week to assess process stability and microbial performance. The digesters were arranged into two experimental pairs based on feedstock type. One pair was fed on maize and the other on wheat, both of which are routinely used at the AD plant and are representative of typical energy crops for anaerobic digestion. Following an initial feedstock acclimation period, hydrogen injection was applied to one digester within each feedstock pair, resulting in four parallel operating regimes:

- maize with hydrogen injection
- maize control (no hydrogen injection)
- wheat with hydrogen injection
- wheat control (no hydrogen injection)

This configuration enabled direct comparison of hydrogen-assisted and conventional digestion performance for each feedstock under otherwise equivalent operating conditions.

Figure 2: Experimental set up of Laboratory digester system used for hydrogen-assisted anaerobic digestion experiments.

Trace elements were added to the digesters between day 12-15 to make up an additional strength of Co (0.5 mg L^{-1}), Ni (0.5), Fe (0.5), Se (0.1), Mo (0.1) and W (0.1), due to the observed pH decrease to 7.4 and a total ammoniacal nitrogen content of 3000 mg N L^{-1}. Trace element solutions were added weekly thereafter to maintain their concentrations and support microbial activity. The VFA concentrations were reduced from a peak level of 6000-7000 mg COD L^{-1} to <1000 mg COD L^{-1} within two weeks (Figure 3), demonstrating recovery of process stability and a return to efficient digestion performance. The total VFA remained below 500 mg COD L^{-1} thereafter.

3.2 Experimental Outcomes

The experimental results demonstrate that hydrogen injection significantly enhanced biogas quality and biomethane yield, while maintaining stable digester performance across both feedstocks.

3.2.1 Volatile Fatty Acids (VFAs)

VFAs initially accumulated to 6000–7000 mg COD L^{-1} by days 12–15, coinciding with a pH decline to 7.4. Following trace-element supplementation, VFAs decreased to <1000 mg COD L^{-1} within two weeks, and remained <500 mg COD L^{-1} for the remainder of the trial (Figure 3). This confirmed full recovery of methanogenic activity prior to hydrogen injection. The similar VFA trajectories across all four digesters indicate that hydrogen injection did not adversely affect process stability or acid–base balance.

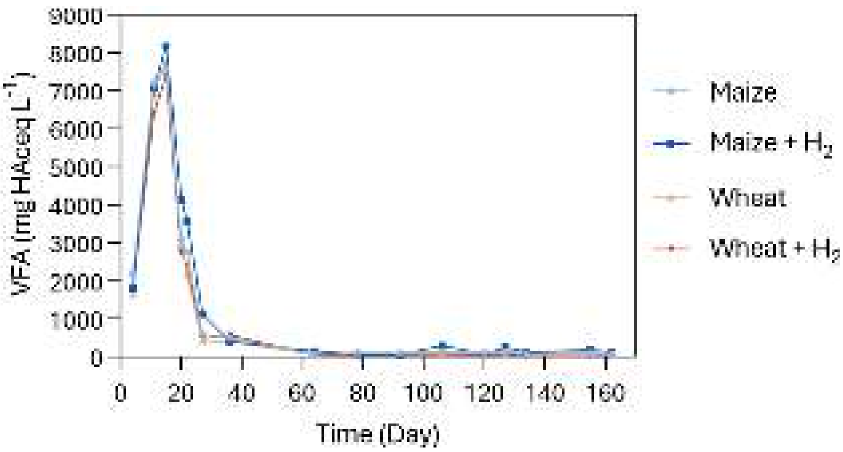

Figure 3: VFA concentrations over the 160 day operating period for maize and wheat fed digesters, with and without hydrogen injection over the operating period.

3.2.2 Digestate Stability and Physicochemical Parameters

Key stability indicators including total ammoniacal nitrogen (TAN), partial alkalinity (PA), intermediate alkalinity (IA), total alkalinity (TA), solids content, and IA:PA ratio, remained within stable operating ranges throughout the experiment. PA reflects the bicarbonate buffering capacity, whereas IA represents intermediate acids such as VFAs, making the IA:PA ratio a useful indicator of whether acid production is being effectively buffered. In operational terms, a low IA:PA ratio shows that methanogens are keeping pace with acid production, preventing accumulation of VFAs and maintaining stable pH. A rising ratio would indicate that acids are building up faster than they are being converted, signalling early-stage process imbalance or potential inhibition. As shown in Figure 4, there were no significant differences observed between hydrogen-assisted digesters and their respective controls. This confirms that hydrogen injection did not disrupt acid–base balance, buffering capacity, or solids degradation performance. All digesters operated under stable mesophilic conditions following the initial trace-element correction.

TAN concentrations remained well below inhibitory thresholds for mesophilic digestion, indicating that ammonia toxicity was not a limiting factor. Alkalinity fractions (PA, IA, TA) showed consistent buffering capacity across all reactors, with IA:PA ratios remaining within the accepted stability range (<0.3–0.4), demonstrating that no accumulation of intermediate acids occurred following hydrogen addition. Similarly, TS, VS and VS:TS ratios were comparable between treatments, confirming that hydrogen injection did not alter solids destruction efficiency or organic matter conversion.

All digesters operated under stable mesophilic conditions following the initial trace-element correction, and no secondary instability events were observed. Collectively, these results demonstrate that hydrogen dosing did not negatively impact digester stability or physicochemical performance.

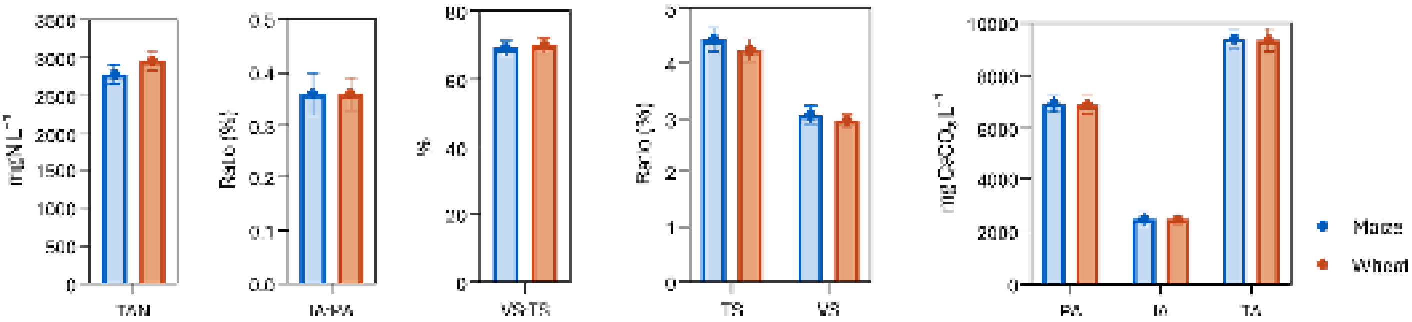

Figure 4: Comparison of stability and solids parameters for maize- and wheat-fed digesters. Grouped bar charts showing (i) total ammonia nitrogen (TAN), (ii) IA:PA ratio, (iii) VS:TS ratio, (iv) total solids (TS) and volatile solids (VS), and (v) alkalinity fractions (PA, IA, TA) for maize- and wheat-fed digesters. Bars represent mean values with standard deviation (SD).

3.2.3 Biomethane Production

Hydrogen injection had a clear and sustained positive effect on biogas quality and biomethane yield. As shown in Figures 5 and 6, biomethane concentration and specific methane production (SMP) increased markedly following the onset of hydrogen dosing. After initial stabilisation associated with trace-element addition, biomethane content rose steadily throughout the operating period. In the maize-fed digester, biomethane concentration increased from 54% at baseline to 83%, while the wheat-fed digester increased from 54% to 82%.

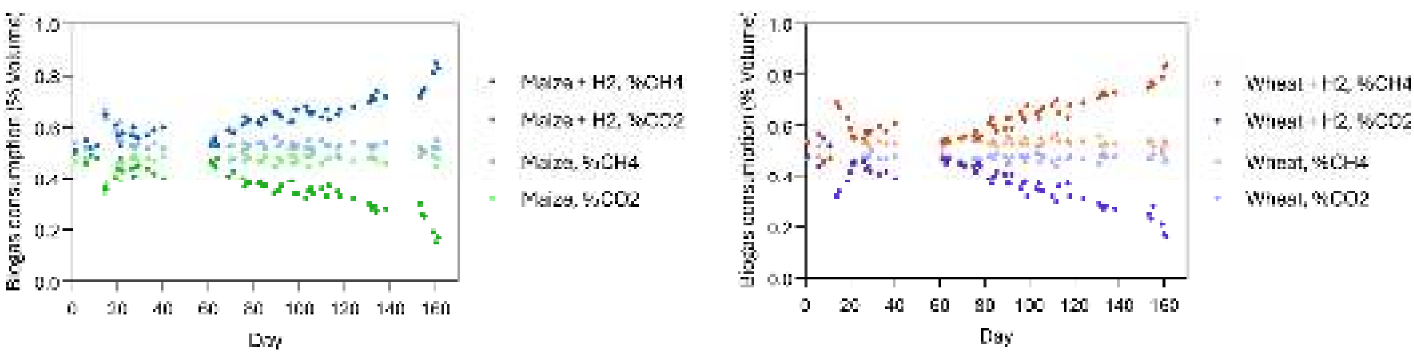

Figure 5: Effect of hydrogen injection on methane and carbon dioxide concentrations in maize- and wheat-fed digesters. Time-series plots show the evolution of CH_4 and CO_2 concentrations for hydrogen-assisted and control digesters. Hydrogen dosing resulted in a sustained increase in methane content and a corresponding decrease in CO_2, with final methane concentrations reaching 82-83% compared with 54% in the controls.

SMP increased by 55% in both hydrogen-assisted digesters relative to their respective controls, demonstrating a substantial uplift in methane generation per unit of volatile solids degraded. These improvements reflect genuine biological utilisation of hydrogen rather than changes in gas dilution or measurement artefacts. No residual hydrogen accumulation was detected in the biogas stream, indicating efficient microbial uptake and safe operating conditions.

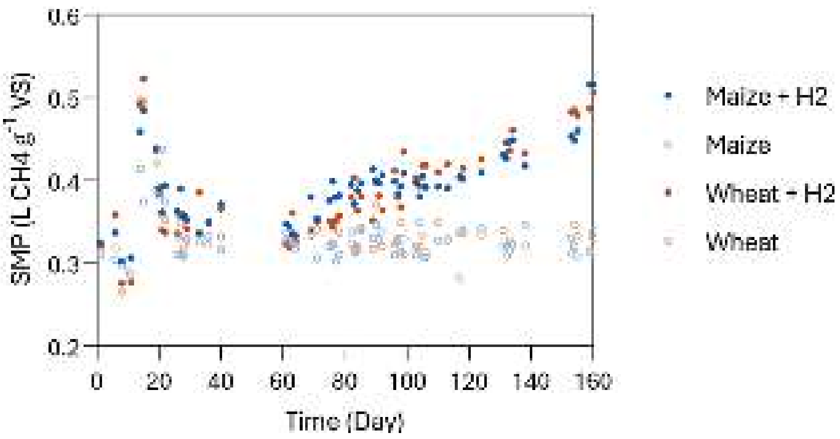

Figure 6: Specific methane production (SMP) for maize- and wheat-fed digesters with and without hydrogen injection. Time-series data show SMP (L CH_4 g $^{-1}$ VS) across the operating period.

The observed relationship between pH and CO_2 partial pressure aligned closely with thermodynamic model predictions (Figure 7), supporting the interpretation that hydrogenotrophic methanogenesis was responsible for the increased methane fraction through in situ CO_2 conversion. As pH increased during stable operation, CO_2 partial pressure declined in a manner consistent with the expected equilibrium behaviour, indicating that the microbial community was effectively utilising the injected hydrogen to convert dissolved CO_2 into methane. This strong agreement between measured and modelled values provides confidence that the underlying biochemical pathways were functioning as intended and that the system was operating within predictable thermodynamic limits.

Model outputs indicated theoretical methane contents of 88% for maize-fed digesters and 89% for wheat-fed digesters under the tested conditions. The experimental results approached these upper limits, demonstrating strong potential for further optimisation of hydrogen mass transfer and reactor operation.

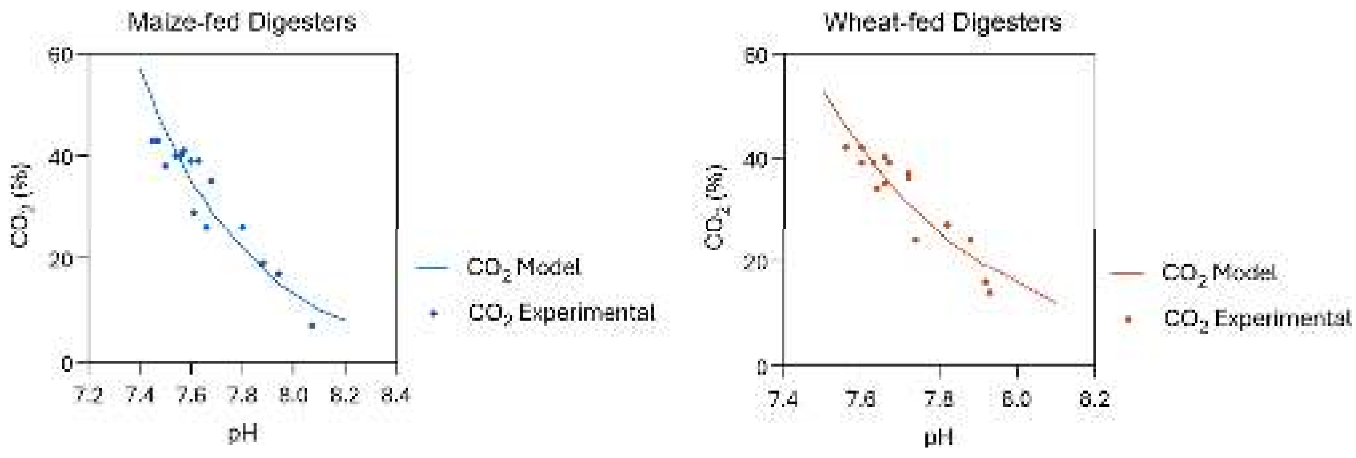

Figure 7: Comparison of experimental and modelled CO_2 concentrations as a function of pH. Scatter points represent measured CO_2 values from maize- and wheat-fed digesters, with solid lines showing the corresponding model predictions.

3.2.4 Key Conclusions of Laboratory Scale Experimental

Hydrogen injection delivered a clear and sustained uplift in biomethane production across both maize- and wheat-fed digesters. Biomethane concentrations increased from 54% at baseline to 82–83% under hydrogen-assisted operation, with methane yield rising by 55% relative to the control digesters. These improvements were achieved while maintaining stable mesophilic digestion, with no renewed accumulation of intermediates and consistent buffering capacity throughout the operating period. This demonstrates that the uplift in biomethane output was achieved without compromising process stability or operational robustness.

The strong correspondence between measured CO_2 partial pressures and the thermodynamic model (Figure 7) confirms that the increase in biomethane content resulted from predictable in situ CO_2 conversion via hydrogenotrophic pathways. As pH increased, CO_2 partial pressure declined in line with modelled equilibrium behaviour, indicating efficient microbial utilisation of the injected hydrogen. This alignment provides confidence that the system was operating close to its expected biochemical limits and that the observed performance improvements were driven by genuine biological methanation rather than artefacts of gas mixing or dilution.

Model predictions indicated theoretical biomethane contents of 88% for maize-fed digesters and 89% for wheat-fed digesters under the tested conditions. The experimental results approached these upper limits, demonstrating that the reactors were performing near their maximum biomethanisation potential. Although the full theoretical maxima were not reached due to unavoidable operational interruptions, the proximity of the measured values to the modelled limits highlights the effectiveness of the hydrogen dosing strategy and the responsiveness of the microbial community.

From a system-level perspective, the laboratory findings demonstrate that significantly increasing biomethane content at source is both technically achievable and biologically stable under controlled conditions. Hydrogen injection consistently elevated biomethane concentrations from a baseline of 54% to around 80%, representing a substantial improvement in gas quality within the digester itself. This uplift directly reduces the proportion of CO_2 in the raw biogas stream, indicating clear potential to lower the burden on downstream upgrading. This laboratory work establishes the core evidence base showing that hydrogen-assisted biomethanisation can materially enhance biomethane production at source and deliver a higher-value gas stream before any external processing is applied.

4. On-Site Demonstrator Testing

Small-scale on-site testing was undertaken at an operational AD facility to assess the practical implementation of hydrogen injection under real-world conditions. The on-site work was designed to demonstrate the hydrogen injection concept using a contained test system, without direct integration with the main digester, while addressing safety, environmental, and operational considerations relevant to commercial AD assets. The testing was carried out within a mobile laboratory installed at the AD facility for the project duration.

4.1 On-Site Planning, Risk Assessment and Permitting

On-site small-scale testing at the AD facility was undertaken following a structured planning and risk management process to ensure that all activities could be carried out safely, compliantly, and without impact on core site operations. Given the introduction of hydrogen handling and experimental equipment within a live AD environment, a systematic approach to hazard identification, risk assessment, and control definition was adopted at the design stage and carried through to installation and operation.

To support this process, a detailed process and instrumentation diagram (P&ID) was developed for the testing rig, defining the configuration of gas supply, pressure regulation, reactors, instrumentation, and safety systems. The P&ID formed the basis of a formal hazard identification (HAZID) exercise, in which the test system was analysed as four discrete nodes. This structured review enabled systematic identification of potential hazards associated with hydrogen and carbon dioxide handling, pressure control, and operational interfaces. All risks identified through the HAZID process were mitigated to acceptable levels through targeted modifications to the test rig design and the definition of specific operational procedures. These mitigation measures were embedded within the system design and operating controls, with detailed actions and findings captured within the supporting HAZID documentation.

In parallel, a DSEAR assessment was undertaken to evaluate the risks associated with flammable atmospheres arising from hydrogen use. The assessment defined hazardous area zones associated with the test system and informed equipment selection, electrical classification, ventilation arrangements, gas detection, and emergency shutdown functionality. Hazardous area classification drawings and associated controls were incorporated into both the physical design of the system and the operational procedures governing its use.

The outcomes of the P&ID review, HAZID, and DSEAR assessments were consolidated within a comprehensive Risk Assessment and Method Statement (RAMS) developed by HydroStar. The RAMS governed the delivery, installation, commissioning, and operation of a containerised mobile laboratory housing the test equipment. It addressed hazards associated with site access, lifting and handling operations, temporary works, utilities connections, electrical systems, and the operation of anaerobic digestion reactors within the laboratory environment. All lifting operations were undertaken in accordance with LOLER requirements using certified contractors, and the laboratory layout was designed to maintain safe separation from existing operational areas.

Environmental and regulatory considerations were addressed through a formal trial request and environmental risk assessment prepared for the AD facility. The proposed testing activities were reviewed against the site's existing Environmental Permit, and it was confirmed that the work fell within the scope of permitted research and innovation activities. No additional environmental permit was required, provided that testing was confined to a sealed, contained laboratory system operating independently of the main AD process.

The test system was designed as a fully contained, closed-loop process with no routine gaseous or liquid emissions. Digestate used within the laboratory reactors was sourced from the site and returned to the main AD process following testing, ensuring that no new waste streams were introduced. Secondary containment and existing site drainage controls provided additional protection against accidental releases, and all activities were conducted in alignment with the AD facilities environmental management and emergency response procedures.

Overall, the structured application of P&ID-led hazard identification, DSEAR assessment, and RAMS development ensured that small-scale testing could be undertaken safely within an operational AD facility while maintaining regulatory compliance and protecting the integrity of both the site and the wider gas network. This approach provides a clear and transferable framework for implementing hydrogen-assisted AD testing at other operational sites.

4.2 On-Site Demonstrator Test System Design

The testing set up was housed within a containerised mobile laboratory installed within the operational AD facility. Locating the system on site enabled access to representative digestate, utilities, and the operational context of a commercial AD plant, while maintaining physical and operational separation from the main digester, biogas upgrading, and gas injection infrastructure.

The test reactors were designed as vertical, mechanically mixed vessels suitable for controlled anaerobic digestion studies at small scale. The mechanical design of the reactor vessels, including vessel geometry, internal mixing arrangement, and supporting frame, is illustrated in Figure 8. The reactors were configured as closed, contained units to enable controlled hydrogen and carbon dioxide injection and monitoring of gas composition without any direct connection to the site's primary digestion or biogas handling systems.

Instrumentation was incorporated to support continuous monitoring of key process variables relevant to experimental evaluation, including gas flow, gas composition, temperature, pressure, and pH. The test system layout enabled shared use of analytical instrumentation across reactors, allowing sequential measurement while maintaining comparability between operating regimes. Data acquisition was time-stamped to enable correlation between operating conditions, gas injection profiles, and observed process responses.

Digestate used within the test reactors was sourced from the host AD facility to ensure biological relevance. Following testing, digestate was returned to the main AD process, allowing the test system to operate without introducing additional waste streams. The overall arrangement functioned as a closed-loop experimental system operating alongside, but independent from, the main AD plant. Photos of the experimental set up can be seen in Figure 9.

Figure 8: CAD representations of the anaerobic digestion test reactor vessels used within the on-site testing programme.

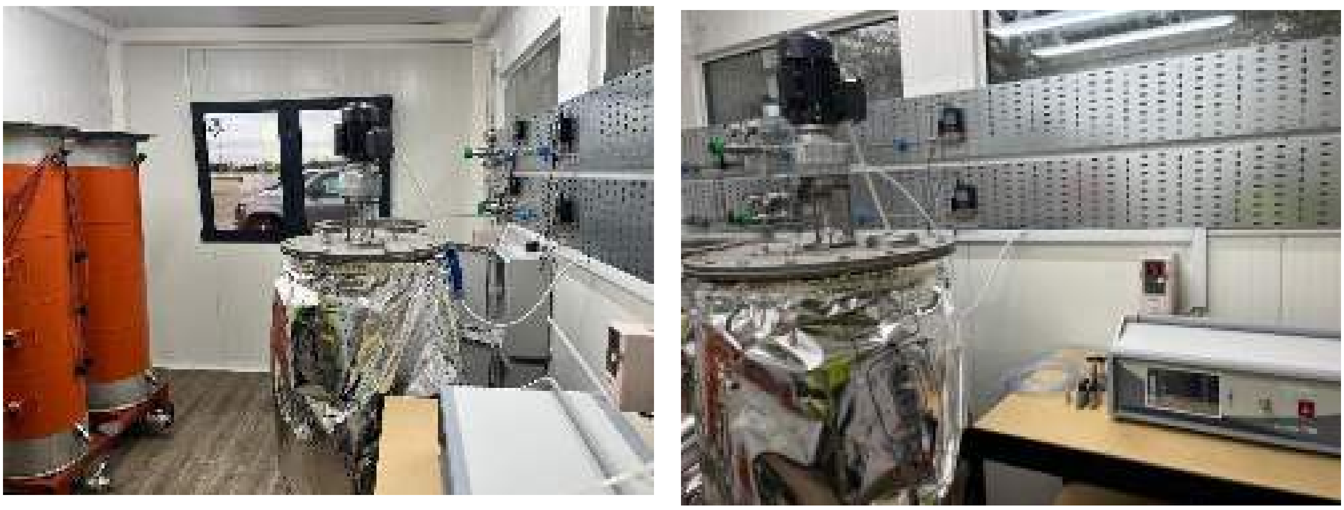

Figure 9: Experimental Set up within a containerised mobile laboratory installed within the AD facility.

Overall, the design and integration of the small-scale test system provided a practical and flexible platform for evaluating hydrogen-assisted anaerobic digestion within an operational context. By focusing on experimental controllability, biological relevance, and physical separation from core plant assets, the system supports generation of transferable learning applicable to future AD optimisation studies.

4.3 On-Site Demonstrator Methodology

Two identical anaerobic digesters were operated in parallel throughout the trial period. Each reactor had a working volume of approximately 0.10 m^3 and was filled using fresh digestate obtained from the primary digester at the AD facility. One reactor was used for testing the effects of hydrogen injection on the AD process and the second was used as a control with no hydrogen being injected. Both digesters were maintained under equivalent operating conditions throughout the experimental programme to ensure that any observed differences in gas composition or process behaviour could be attributed to hydrogen addition.

The digesters were operated under mesophilic conditions, meaning they were maintained within the moderate temperature range (typically 35-45 °C) where most anaerobic digestion microorganisms perform optimally, with a target operating temperature of approximately 43 °C. Continuous low-speed mixing was used to maintain homogeneous reactor conditions and improve gas-liquid contact within the digestate. Hydrogen was supplied to the test digester through a controlled injection system equipped with a calibrated flow controller capable of delivering hydrogen flow rates between 0 and 1 L min^{-1}. Gas composition measurements were obtained using a calibrated biogas analyser capable of monitoring biomethane, carbon dioxide, hydrogen, and hydrogen sulphide.

Prior to the start of testing, approximately 250 L of fresh digestate was collected from the operational anaerobic digestion plant. Feedstock mixtures representative of commercial AD operation were prepared and weighed into daily feeding batches for each digester. The daily feedstock composition per digester comprised:

- Wheatfeed
- Pig slurry
- Poultry litter
- Cow manure
- Crop rye
- Maize silage

This provided a total daily feed input of approximately 1.35 kg per digester. Feedstock selection was intended to replicate the mixed agricultural substrates commonly encountered in commercial anaerobic digestion systems.

An initial seven-day stabilisation period was undertaken prior to the start of hydrogen injection in order to establish stable anaerobic digestion conditions and confirm that both digesters showed a comparable baseline. During this phase, both digesters were operated under identical conditions without hydrogen addition. The reactors were fed daily at consistent loading rates using the prepared feedstock mixture, while temperature, pH, gas composition, and biogas flow rates were monitored regularly throughout the operating period.

The purpose of the stabilisation phase was to allow the microbial communities within the digesters to acclimatise to the operating conditions and feedstock composition prior to hydrogen injection trials. Methane concentration, carbon dioxide concentration, hydrogen sulphide concentration, reactor temperature, and pH were recorded at regular intervals to establish baseline operating behaviour for both digesters. The stabilisation data obtained during this phase was subsequently used as the reference condition for evaluating the impact of hydrogen injection during the experimental testing programme.

4.4 On-Site Demonstrator Testing Results & Analysis

Prior to hydrogen injection testing, both digesters underwent a seven-day stabilisation period to establish comparable baseline anaerobic digestion performance. During this phase, methane concentrations in both the control and testing digesters increased progressively following reactor filling and acclimatisation to the feedstock mixture and operating conditions. Initial methane concentrations of approximately 39% CH_4 were recorded immediately following reactor commissioning, after which methane production increased steadily over the first three days of operation.

By approximately Day 3, both digesters had reached a stable methane concentration of approximately 55% CH_4 and remained within a narrow operating range for the remainder of the stabilisation period (See Figure 10). Minimal variation was observed between the control and testing digesters throughout this phase, indicating that both systems exhibited similar biological activity and digestion performance prior to hydrogen injection

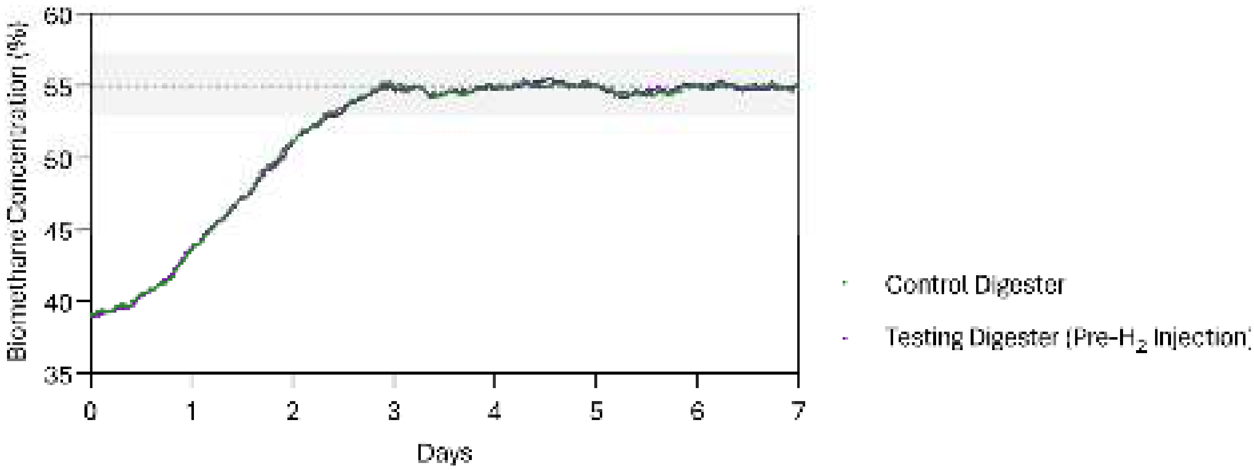

Figure 10: Biomethane concentration profiles for the control and testing digesters during the seven-day stabilisation period prior to hydrogen injection. The dashed line indicates the 55% CH_4 target baseline, while the shaded region represents the stable operating range.

Following completion of the stabilisation phase, hydrogen injection trials were undertaken at flow rates of 0.25, 0.50, and 0.75 L min^{-1} for a fixed injection duration of four hours. Across all test scenarios, the hydrogen-injected digester demonstrated a clear increase in biomethane concentration relative to the untreated control digester, confirming that hydrogen addition promoted biological methanation within the reactor system.

As shown in Figure 11, all hydrogen injection scenarios resulted in an increase in biomethane concentration during and immediately following the hydrogen dosing period. At the lower hydrogen injection rate of 0.25 L min^{-1}, biomethane concentration increased from the baseline level of approximately 55% to peak concentrations of approximately 64-68% before gradually declining back towards baseline conditions following cessation of hydrogen injection. The repeated 0.25 L min^{-1} trial produced a similar response profile, demonstrating reasonable short-term repeatability within the experimental system.

Increasing the hydrogen injection rate to 0.50 L min^{-1} resulted in a larger biomethane enrichment response, with biomethane concentrations reaching approximately 73% CH_4. The highest injection rate of 0.75 L min^{-1} produced the greatest biomethane enhancement, with peak biomethane concentrations approaching 76% CH_4 during the post-injection response period.

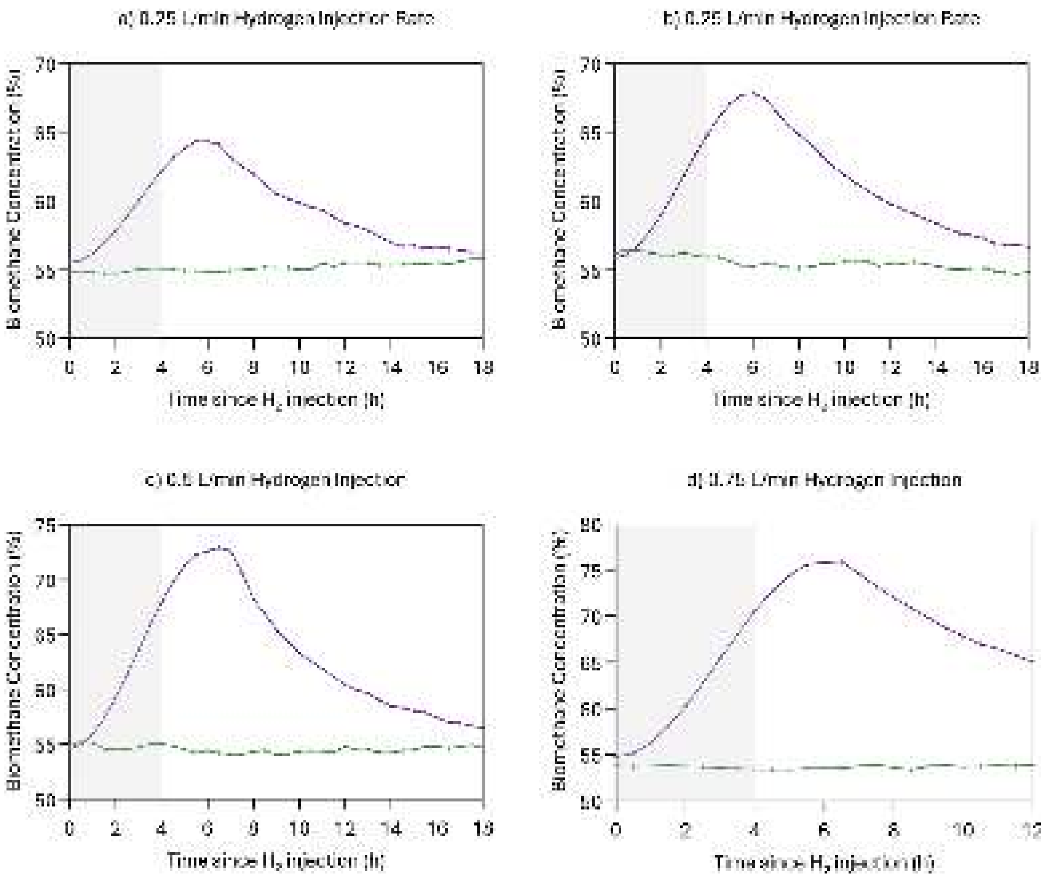

Figure 11: Biomethane concentration response of the testing digester and control digester during hydrogen injection trials at varying hydrogen flow rates. a) 0.25 L min $^{-1}$hydrogen injection trial 1; b) 0.25 L min $^{-1}$hydrogen injection trial 2; c) 0.50 L min $^{-1}$ hydrogen injection; and d) 0.75 L min $^{-1}$ hydrogen injection. The shaded region indicates the four-hour hydrogen injection period. Graphs (a) and (b) are repeat 0.25 L min $^{-1}$ trials.

The recovery behaviour observed following hydrogen injection also varied with injection rate. As illustrated in Figure 11, lower hydrogen flow rates returned relatively rapidly towards baseline conditions following cessation of hydrogen dosing. However, at higher hydrogen injection rates, the decline back towards baseline biomethane concentrations occurred more gradually, indicating an extended biological response within the reactor system. At higher hydrogen loading rates, more hydrogen remains dissolved and the microbial community needs longer to adapt, which can delay the return to normal methanogenic activity.

4.5 On-Site Demonstrator Testing Phase Conclusions

The on-site small-scale testing programme demonstrated that controlled hydrogen injection can increase biomethane concentration within an anaerobic digestion process under representative operating conditions. Across all hydrogen injection scenarios, the testing digester exhibited a clear increase in biomethane concentration relative to the untreated control digester, indicating that hydrogen-assisted biomethanisation was occurring within the system. The results showed a relationship between hydrogen injection rate and biomethane enhancement. Increasing hydrogen flow rate generally resulted in higher peak biomethane concentrations, with the 0.75 L min^{-1} trial producing the highest observed biomethane concentration during the testing programme.

Although increased biomethane concentrations were observed, the peak values achieved during the on-site demonstrator trials remained below the upper biomethane concentrations previously achieved during laboratory-scale testing at the University of Southampton. This is likely to be associated with the relatively short four-hour hydrogen injection duration used during the demonstrator trials, which may not have allowed sufficient time for the biological system to approach a fully stabilised hydrogen-enhanced operating condition. The observed trends suggest that longer injection durations and extended operating periods could potentially result in further biomethane enrichment, although additional testing would be required to confirm this.

Differences were also observed in the recovery behaviour following hydrogen injection. Lower hydrogen injection rates returned more rapidly towards baseline biomethane concentrations, whereas higher injection rates exhibited a more prolonged elevated biomethane response following the end of injection. This suggests that hydrogen utilisation and recovery dynamics may vary depending on injection rate and system conditions.

Overall, the testing phase demonstrated the feasibility of hydrogen-assisted biomethanisation at small demonstrator scale and provided operational data to support future optimisation and further experimental investigation of the process under longer-term operating conditions. Under longer-term or continuous hydrogen dosing, we would expect the system to move closer to a fully stabilised hydrogen-enhanced operating state, characterised by higher sustained biomethane concentrations, more consistent conversion of CO_2, and a smoother recovery profile following changes in hydrogen availability.

5. Widescale implications across the Gas Network

The project demonstrates that hydrogen-assisted biomethanisation has the potential to materially enhance the performance, efficiency, and carbon intensity of biomethane supplied to the gas distribution network. By increasing biomethane content at source and reducing the proportion of CO_2 in the raw gas stream, the enhanced process supports more efficient upgrading and delivers a more consistent, higher quality gas to the network. Higher methane concentrations correspond to a higher calorific value, meaning that in principle the upgraded gas would require less propane to meet CV specifications. The combined laboratory, modelling and on-site findings show that the process is technically feasible and can operate upstream of existing gas network infrastructure. Further commercial-scale testing is required to confirm residual hydrogen management and full compliance with network-entry requirements.

When deployed across the wider AD portfolio, the enhanced process offers a pathway to increase renewable gas availability, improve network resilience, and support long-term decarbonisation objectives. The following subsections outline the implications for network integration, economic and environmental performance, and the steps required for widescale implementation.

5.1 Integration of the enhanced process into the existing gas infrastructure

Hydrogen-assisted biomethanisation integrates well with existing biomethane-to-grid infrastructure because the conversion of CO_2 to biomethane occurs entirely within the digester, upstream of any network interface. As a result, the upgraded gas stream does not introduce hydrogen into the grid. The enhanced process increases the methane content of the biogas leaving the reactor, meaning the raw gas enters the upgrading system with a higher calorific value and a lower CO_2 fraction than conventional AD. This provides a higher-quality feed gas for the scrubbing system, which still removes impurities as normal.

As the methane fraction is higher, the upgraded biomethane would, in principle, require less propane to meet CV specifications, although the exact impact depends on the upgrading technology, site-specific CV targets, and any blending strategies used by the producer. In cases where total biogas flow increases as a result of hydrogen-assisted operation, the absolute propane requirement could rise even if the per-unit CV uplift reduces the proportional need for enrichment relative to the CO2 released within the biomethane process.

Operationally, the process requires no modification to network pressure management, metering, or downstream pipeline infrastructure. Integration does, however, require appropriate hydrogen storage and dosing systems that comply with ATEX and pressure-systems regulations, alongside standardised monitoring of pH, CO_2 partial pressure, and gas composition to ensure stable operation within defined limits.

5.2 Economic and Environmental Impact Assessment

Analyses were undertaken on the environmental and economic impacts of implementing hydrogen optimised biomethane. This focussed on analysing the absolute impacts along with a comparison to the counterfactual approach of building further infrastructure to increase biomethane capacity.

5.2.1 Environmental Impact Assessment

The direct environmental benefits of increasing biomethane production from existing infrastructure were assessed by comparing the additional biomethane with an equivalent amount of fossil natural gas. For this assessment, a plant producing 1,000 standard cubic metres of biogas per hour was modelled.

Assuming an average biogas energy content of 6 kWh per standard cubic metre, the annual energy output would be:

$1{,}000 \times 24 \times 365 \times 6 = 52{,}560{,}000$ kWh = 52.56 GWh per year

A 50% increase in biomethane output would provide an additional 26.28 GWh per year. All emissions in this calculation are expressed as carbon dioxide equivalent emissions. This means the total climate impact is shown as the amount of carbon dioxide that would have the same effect. According to the Government Conversion Factors, natural gas produces 0.18254 kilograms of carbon dioxide equivalent emissions for each kWh through combustion and a further 0.0311 kilograms for each kWh through Well to Tank emissions. The total emissions used in this assessment are therefore 0.21364 kilograms of carbon dioxide equivalent emissions for each kWh.

Lifecycle analysis indicates an assumed carbon intensity of 1.7 kilograms of carbon dioxide equivalent emissions for each kilogram of green hydrogen produced.

To calculate the hydrogen required to produce one kWh of additional methane, the mass of methane corresponding to one kWh was first calculated:

1. 1 kWh is equal to 3.6 MJ
2. The Higher Heating Value (HHV) of methane is approximately 55.55 MJ/kg
3. Mass = energy ÷ Higher Heating Value
4. Therefore, $3.6 \div 55.55 = 0.0648$ kg CH_4/kWh

The hydrogen requirement was then calculated using the methanation reaction:

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

One mole of methane has a mass of approximately 16 g. Producing one mole of methane requires four moles of hydrogen gas, with a combined mass of approximately 8 g. The mass of hydrogen required is therefore 50% of the mass of methane produced.

The theoretical hydrogen requirement is 0.0648 × 0.50 = 0.0324 kg H_2/kWh. Using the assumed green hydrogen carbon intensity of 1.7 kilograms of carbon dioxide equivalent emissions for each kilogram of hydrogen, the emissions associated with the hydrogen are 0.0324 × 1.7 = 0.0551 kilograms of carbon dioxide equivalent emissions for each kWh.

The theoretical net carbon saving is approximately 0.15855 kilograms of carbon dioxide equivalent emissions for each kWh.

0.15855 * 1000000 * 26.28 = 4,166,431.2 kgCO2/year

= 4,167 tCO2/year

The factor of 1,000,000 converts the additional annual output from GWh to kWh because the carbon saving is calculated for each kWh. For an additional annual biomethane output of 26.28 GWh, this gives approximately 4.17 million kilograms, or 4,167 tonnes, of carbon dioxide equivalent emissions per year.

This is a theoretical best case estimate that assumes all of the supplied hydrogen is converted. If the conversion efficiency is lower, more hydrogen would be required and the net carbon saving would be reduced. Further environmental benefits may also arise from avoiding the construction of additional AD capacity. Construction of a new 1,000 scmh plant is estimated to produce approximately 400 to 700 tonnes of carbon dioxide equivalent emissions, depending on the plant design and site requirements. Increasing production from existing infrastructure could therefore avoid some or all of these construction related emissions.

5.2.2 Economic Impact Assessment

The economic impacts can be assessed both from a capital savings perspective, but also from on ongoing operational perspective.

The capital savings benefit is clear. If the percentage increase in biomethane output is compared to the capital expenditure of building a new plant, the increase in output can be equivalent to multiple millions of pounds of saving at each plant. For example, the cost of building a 1000scmh plant sees a range of £8-15m, depending on the specific feedstocks used and the gas upgrading requirements. A 50% uplift was used as a high-performance modelling assumption, broadly aligned with the sustained laboratory result. The demonstrator trials produced lower peak-based uplifts of up to approximately 38.4%. Under the 50% modelling assumption, the avoided cost of building equivalent new capacity would be approximately £4 million to £7.5 million per plant.

The avoided investment cost saving is therefore clear, however this must be compared against the operational costs of using hydrogen, which is currently expensive as green hydrogen, to increase biomethane yields. Discounted cash flow analyses were used, which considered the investment required to retrofit hydrogen injection equipment to existing AD plants along with the ongoing cost of hydrogen against the increase in revenue which could be attained from the biomethane.

The avoided investment cost was also considered and integrated into the model, being apportioned across the lifetime of the plant. An essential further part of the model is the avoided operational costs associated with operating a new plant instead of increasing an existing plant. Literature highlighted that operational expenses can total 15-25% of the capital expenditure of an AD plant annually, which based off the £8-15m capital expenditure delivers an operational expenditure ranging from £1.2-£3.75m annually. The marginal increase from maintenance of a hydrogen injection system would be marginal instead of the operational costs of an entirely new plant, therefore this saving has also been integrated into the model.

Therefore a techno-economic model was built, having the functionality to adjust both the technical and financial indicators as shown below. This techno-economic model can be also be used alongside real life data or alternatively the simulation model developed as part of this project to provide the technical parameters such as percentage increase, as shown within Figure 12.

TECHNICAL INPUTS		
Plant output capacity	1000	scmh
Output increase	50%	
Capacity factor	30%	
FINANCIAL INPUTS		
Sale price of methane	7.33	p/kWh
Sale price of methane	0.8063	[illegible]
Hydrogen cost	6.85	[illegible]
Plant opex cost	25%	
Capex scenario	High	
Depreciation term	20	years
Inflation rate	2.00%	
Project lifespan	20	years
Discount rate	8%	
Tax rate	25%	
Grant percentage	30.00%	
Loan percentage	0.00%	
Period of loan	15	years
Pre-tax loan interest	5.00%	

TECHNICAL OUTPUTS		
Operational increase	500.00	scmh
Hydrogen demanded	179.80	kg/h
Annual methane increase	1314000	scm
Lifetime methane increase	26280000	scm
FINANCIAL OUTPUTS		
Total CAPEX	£100,000	
Lifetime OPEX	£79,816,254	
Total Lifetime Cost	£79,816,254	
IRR	20.0%	
Payback time	4	
NPV	£ 120,914.50	

Figure 12 – Technoeconomic model input/output parameters

As with the environmental analyses above, a 1000scmh plant was used to run analyses on the economic impacts. A natural gas price of 7.33 p/kWh was used as a modelling proxy, based on the average domestic gas unit rate under the Ofgem Energy Price Cap from 1 July to 30 September 2026. This is a consumer price rather than a confirmed biomethane producer revenue, so plant-specific biomethane sale prices should be assessed separately. The increase in biomethane output was also modelled at 50%, with a conservative initial capacity factor of 30%. The 30% value is representative of an assumed daytime only hydrogen injection window of approximately eight hours, representing a realistic operational pattern for early deployment while avoiding continuous hydrogen supply constraints. Higher capacity factors can be modelled, but these may be limited by hydrogen availability and by the rated capacity of existing upgrading systems.

A sensitivity analysis was undertaken to account for the variability that could be experienced in three of the main model parameters and costs;

- **Natural gas price**
  Variability in market prices can change the rate of return which would be experienced through increasing the biomethane output. Three different values were used, with the baseline being the 7.33p/kWh mentioned above and the other two being a 20% increase in natural gas price (8.80p/kWh) or a 20% decrease in natural gas price (5.86p/kWh)
- **AD plant capital cost**
  Capital expenditure for new infrastructure is an essential input since the avoided capital costs would vary depending on the cost of a new build plant. A high capital cost per 1000scmh of £15m and a low scenario of £8m were used, but then scaled relative to the percentage increase of plant output. So the 50% increase corresponds to a £4-£7.5m avoided cost.
- **AD plant operational cost**
  The avoided operational costs associated with running an entirely new AD plant to increase the green gas by the same output as increasing through hydrogen injection were modelled at a low scenario of 15% of plant capital cost annually, or a high scenario of 25% of plant capital cost annually

Hydrogen price was treated as the independent variable within the analyses and was therefore not fixed to a specific value. The IRR value was fixed to ensure commercial viability, and the hydrogen price was adjusted to identify the range within which commercial viability was met. This hydrogen-price range can then be compared against market rates post-project to determine financial viability. It is also important to note potential capacity constraints. If an upgrading plant is designed for 1000 scmh but hydrogen-assisted biomethanisation increases output to 1500 scmh, the plant may not be able to process the uplift. A review of upgrading capacities across representative sites is recommended as a next step.

The price of hydrogen was then adjusted to determine the cost at which a reasonable Internal Rate of Return (IRR) and Net Present Value (NPV) were achieved. This is significant because for existing AD plants to invest in the technology, there must be a supporting business case. The targeted IRR was 20%, with the corresponding prices of green hydrogen to achieve this value being shown numerically in Table 1 and visually in Figure 13.

Capex scenario	Opex scenario	Natural Gas price	Green hydrogen price (£/kg)
High	High	Baseline	£6.90
		High	£7.40
		Low	£6.50
	Low	Baseline	£5.37
		High	£5.81
		Low	£4.92
Low	High	Baseline	£4.73
		High	£5.16
		Low	£4.28
	Low	Baseline	£3.88
		High	£4.33
		Low	£3.43

Table 1 – Sensitivity analysis on green hydrogen price required to achieve financial viability of biomethane enhancement – defined as an IRR of 20%

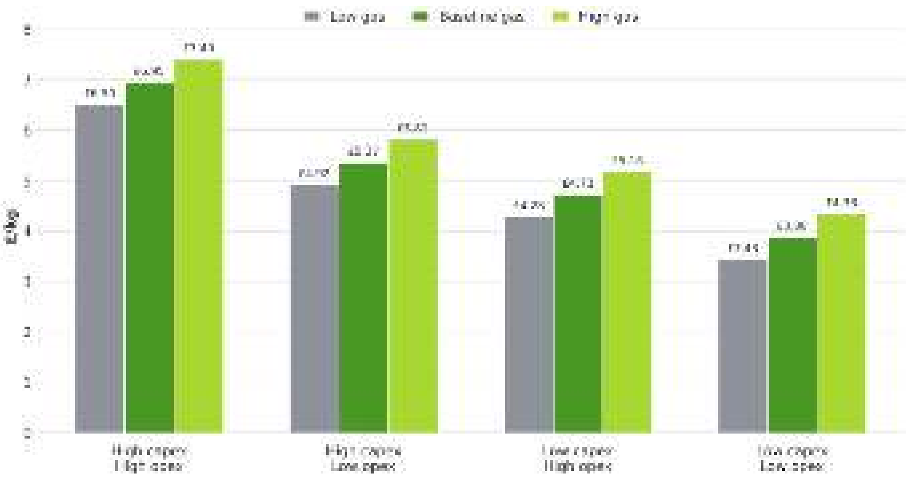

Figure 13 – Sensitivity analysis on green hydrogen price required to achieve financial viability of biomethane enhancement – defined as an IRR of 20%

The results show that the required green hydrogen price to achieve financial viability, understandably, is very responsive to changes in natural gas price. This can be seen in Figure 13 which shows a difference of ~£0.90/kgH2 in all modelled scenarios between the highest and lowest natural gas cost scenarios.

Furthermore, the capital and operational avoided costs have varied impacts on the green hydrogen price required. Some scenarios are already viable under current green hydrogen prices, specifically the high capex scenarios, however other scenarios require future reductions in price to be competitive financially. Therefore existing AD plants must be analysed on a case by case basis to understand the specific economics which support each plant. The developed technoeconomic model facilitates this, and will continue to be developed post project as a tool for supporting biomethane enhancement through hydrogen injection.

5.3 Roadmap for Large-Scale Implementation

The project demonstrated that hydrogen-assisted biomethanisation is technically feasible at both laboratory and demonstrator scale. Four operating scenarios were developed during the project, three from the on-site demonstrator trials, described in Section 4, and one from the continuous laboratory testing undertaken at the University of Southampton, described in Section 3.

When these scenarios are applied across all 22 biomethane plants connected to the WWU network, annual renewable gas delivery could increase from the current 2025/2026 baseline of 1,870 GWh to between 2,311 GWh and 2,790 GWh. The baseline figure represents the combined annual output of all 22 plants during WWU's regulatory year 2025/2026. The four scenarios are summarised in Table 2 and compared in Figure 16.

Scenario	Source	CH_4 achieved	Annual GWh	Uplift	H_2 demand	Households
Current baseline	WWU 2025-26	55% (avg)	1,870	n/a	n/a	163,000
Demonstrator 0.25	0.25 L/min H_2, Day 2 (post-accl.)	68% peak	2,311	+23.6%	13,770 t/yr	201,500
Demonstrator 0.50	0.50 L/min H_2, Day 3	73% peak	2,472	+32.2%	18,800 t/yr	215,500
Demonstrator 0.75	0.75 L/min H_2, Day 4	76% peak	2,588	+38.4%	22,420 t/yr	225,600
Laboratory	Continuous, Univ. of Southampton	82-83% sustained	2,790	+49.2%	28,730 t/yr	243,200

Table 2: Network-scale impact of the four hydrogen-assisted scenarios (2025-26 basis).

The methane percentages used in Table 2 were taken directly from the experimental results. The demonstrator values represent the peak methane concentrations achieved during the four-hour hydrogen dosing periods described in Section 4. The laboratory values represent sustained methane concentrations achieved during the 160-day continuous trials described in Section 3, with methane reaching 82% and 83% in the wheat-fed and maize-fed digesters, respectively. The 82% wheat fed result has been used as the conservative basis for the laboratory projection.

Annual GWh values were calculated by scaling the 1,870 GWh network baseline according to the increase in methane concentration relative to the 55% control baseline. For example, the laboratory projection was calculated as: 1,870 × (82 / 55) = 2,790

Household numbers were scaled using the same ratio from WWU's current estimate of 163,000 homes supplied by biomethane. Hydrogen demand was estimated using the methanation reaction: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

This assumes that every cubic metre of additional methane requires four cubic metres of hydrogen, with hydrogen mass calculated using a density of 0.0899 kg/m³ at standard conditions.

The hydrogen demand values shown in Table 2 represent the theoretical minimum requirement, assuming complete hydrogen conversion efficiency. In practice, some hydrogen remains unreacted and is lost from the system, meaning that the actual hydrogen demand at a commercial scale will be higher.

The short-duration demonstrator trials achieved hydrogen conversion efficiencies between 39% and 72%, with lower efficiencies observed at higher hydrogen injection rates. In this context, conversion efficiency refers to the proportion of injected hydrogen that was biologically converted to methane rather than leaving the system unreacted. Efficiency was highest at the lowest injection rate, at around 72% for the 0.25 L/min case, and fell as the rate increased, to around 49% at 0.50 L/min and 39% at 0.75 L/min. This reflects the reduced contact time and greater mass-transfer limitation as more hydrogen was introduced over the same four-hour dosing period. In contrast, the continuous laboratory trials achieved almost complete hydrogen utilisation, with no residual hydrogen detected in the biogas. The higher conversion efficiency observed during the laboratory trials was primarily attributable to hydrogen recirculation within the experimental system, which kept unreacted hydrogen available for further biological conversion. This operating approach increased hydrogen residence time within the reactor system and improved overall utilisation efficiency. By comparison, the on-site demonstrator trials used single-pass hydrogen dosing during relatively short four-hour injection periods. This highlights the importance of future long-duration testing to determine how closely commercial-scale systems can approach complete hydrogen conversion under practical operating conditions. Higher hydrogen utilisation efficiency would directly reduce the overall hydrogen demand and electrolyser capacity required across the network.

For near-term implementation, the 0.50 L/min demonstrator scenario is used as the planning case. It produced a greater methane increase than the 0.25 L/min scenario, while using hydrogen more efficiently and creating fewer operational concerns than the 0.75 L/min scenario. The 0.50 L/min rate achieved a moderate hydrogen conversion efficiency of around 49%, sitting between the 0.25 L/min case, which converted hydrogen more efficiently at around 72% but delivered a smaller uplift, and the 0.75 L/min case, which produced the highest peak but the lowest conversion efficiency at around 39% and, as the highest dosing rate in the trial, required the most careful pH management. Being based on direct on-site testing at a commercial AD facility, it provides a realistic and defensible planning basis. Under this scenario, annual renewable gas delivery increases to approximately 2,472 GWh, representing a 32.2% increase compared with the current baseline. The number of equivalent households supplied rises from 163,000 to approximately 215,500.

Figure 14: Phased implementation roadmap showing Phase 1 (extended on-site demonstration), Phase 2 (first commercial retrofit), and Phase 3 (network rollout) across 84 months, with milestone markers at the end of each phase.

The laboratory scenario represents a higher-performance operating condition that may be achievable once sustained operation has been demonstrated at the commercial scale. Achieving either scenario requires coordinated development across technical demonstration, hydrogen supply, regulation, and commercial implementation. The proposed phased implementation approach is shown in Figure 14.

5.3.1 Phase 1: Extended on-site demonstration (months 0 to 18)

Phase 1 extends the current AD facility demonstrator from short, four-hour hydrogen-dosing periods to continuous operation over several months. This stage is important for two main reasons.

First, it aims to reduce the gap between the sustained methane concentrations achieved in laboratory trials and the transient peak concentrations observed during on-site demonstrator testing. The laboratory trials achieved stable methane concentrations of 82%-83%, whereas the demonstrator trials reached a maximum of 76% during short-duration dosing. Achieving similar sustained performance at commercial scale would significantly increase renewable gas delivery to the network.

Second, Phase 1 is intended to establish realistic hydrogen conversion efficiencies under long-duration operating conditions. The demonstrator trials showed conversion efficiencies ranging from 39% to 72%, whereas the laboratory trials achieved near-complete hydrogen utilisation due to recirculation within the system. Improving hydrogen conversion efficiency directly reduces hydrogen demand, electrolyser size, and electricity consumption.

Phase 1 should therefore:

- Identify the sustained operating point for commercial-scale digesters
- Validate hydrogen conversion efficiency during long-duration operation
- Determine the operating conditions that maximise biomethane production while minimising hydrogen demand
- Demonstrate integration of a small co-located green hydrogen production unit with the AD system

5.3.2 Phase 2: First commercial retrofit (months 12 to 36)

Phase 2 involves retrofitting hydrogen-injection equipment to one operational biomethane plant within the WWU network. The Demonstrator 0.50 scenario is used as the representative basis for this phase.

Using average values across the 22 WWU plants, Phase 2 would require approximately:

- 855 tonnes of hydrogen per year
- 2.4 million cubic metres of additional biomethane annually
- Around 27 GWh per year of additional renewable gas injection

These values assume complete hydrogen conversion efficiency. Lower conversion efficiencies would require a proportionally greater amount of hydrogen to achieve the same methane output.

Phase 2 is intended to deliver:

- A standardised engineering design package for future retrofits
- A clear regulatory and permitting pathway
- Commercial and regulatory arrangements covering hydrogen supply, GGSS treatment, RGGO certification, and potential savings
- Long-term operational data from a commercial-scale digester

Preferred sites for this phase should have a stable feedstock supply, sufficient space for hydrogen equipment, and strong operator support. The P&ID, HAZID, DSEAR, and RAMS documentation developed during the testing trials can be adapted for future installations.

5.3.3 Phase 3: Network rollout (months 30 to 84)

Phase 3 extends the proven retrofit design across the remaining biomethane plants on the WWU network. A staged deployment approach is recommended, beginning with three to five plants during the first 18 months and progressing to all 22 sites by month 84. Each retrofit is expected to require approximately 12 to 18 months from approval to commissioning.

Under the Demonstrator 0.50 scenario, full deployment would provide:

- An additional 602 GWh of renewable gas annually
- Around 52 million cubic metres of additional biomethane per year
- Hydrogen demand of approximately 18,800 tonnes annually
- Potential for reduced upgrading requirements

If the network achieves the sustained 82% methane concentrations observed during laboratory testing, annual renewable gas delivery could rise to 2,790 GWh, representing a 49.2% increase over the current baseline. In this case, annual hydrogen demand would increase to approximately 28,730 tonnes. Both scenarios are shown in Figure 15.

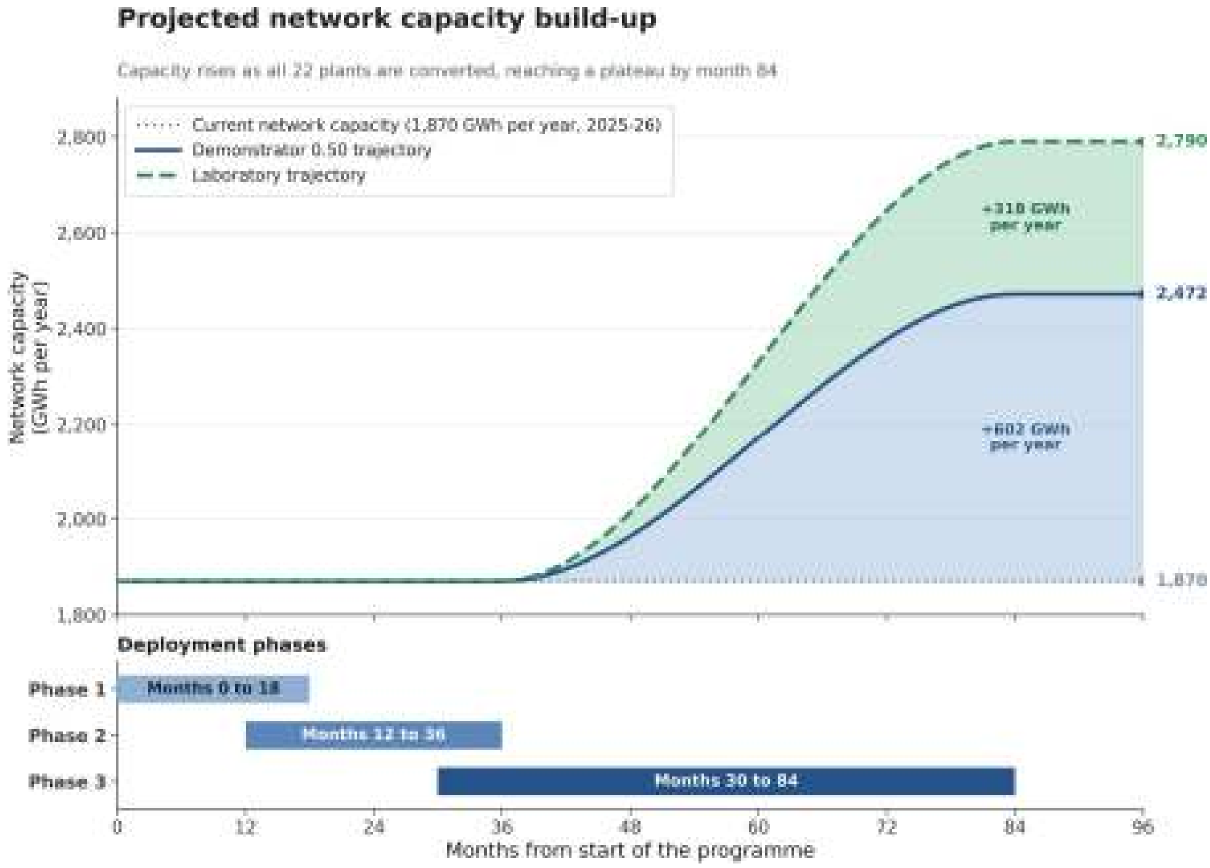

Figure 15: Projected WWU network annual capacity in GWh per year over the 84-month deployment programme. The solid line shows the Demonstrator 0.50 trajectory (planning case, reaching 2,472 GWh once all 22 plants are enhanced). The dashed line shows the Laboratory trajectory (long-term target, 2,790 GWh) if sustained lab-grade performance is achieved at commercial scale.

5.3.4 Strategic Alignment and Recommended Next Steps

The implementation approach aligns with the UK Biomethane Strategy and supports WWU's role in increasing the use of lower-carbon gases that are compatible with existing gas infrastructure. It also provides an early and practical use case for green hydrogen while wider hydrogen blending into gas networks remains constrained by regulation. Figure 16 compares the network impact of all scenarios developed during the project.

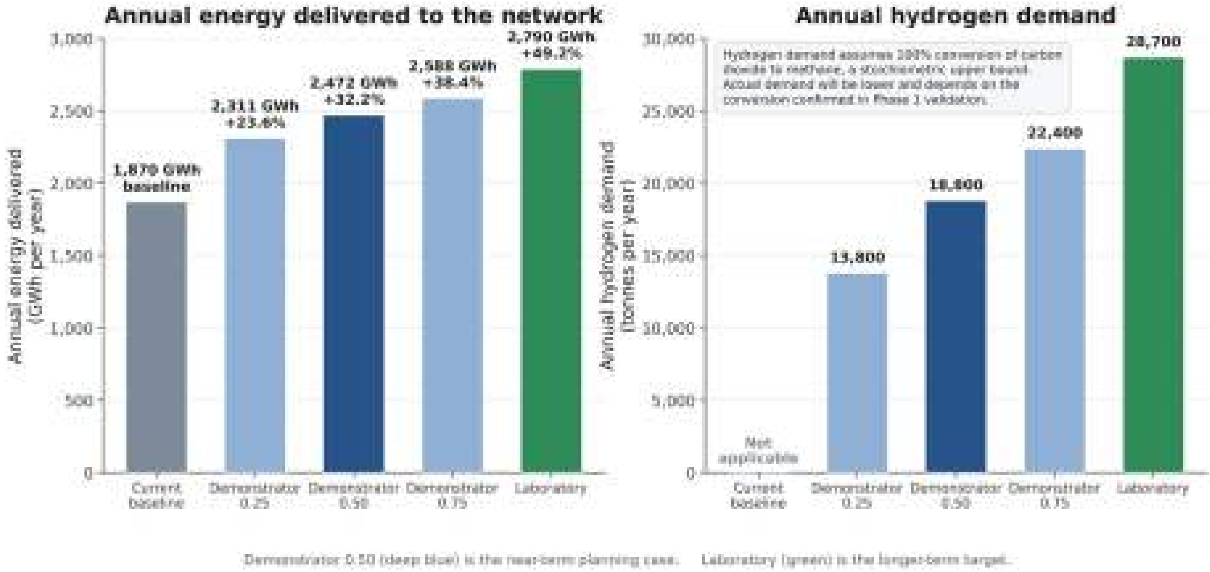

Figure 16: Side-by-side comparison of annual energy delivered to the network (GWh) and annual hydrogen demand (tonnes per year) for the current baseline and the four trial-derived scenarios. Demonstrator 0.50 is highlighted as the near-term planning case, and Laboratory as the longer-term target.

Based on the outcomes of this project, the following steps are recommended for WWU:

- Develop a follow-on project to deliver the extended Phase 1 demonstration, including continuous multi-month operation and a co-located green hydrogen unit.
- Engage with biomethane plant operators across the WWU network to identify suitable Phase 2 sites, prioritising those with stable feedstock supply, available space, and operator support.
- Establish a multi-party working group involving Ofgem, the Health and Safety Executive, the Environment Agency, AD operators, and hydrogen suppliers to progress the regulatory and commercial framework alongside the technical work.

Together, these steps provide a practical, phased route from laboratory and demonstrator testing to wider network deployment, delivering measurable benefits to WWU’s renewable gas portfolio, decarbonisation objectives, and customers.

6. Project Conclusions

This project set out to investigate whether the controlled injection of green hydrogen into the anaerobic digestion process could increase biomethane yield at source, and in doing so reduce the reliance on downstream gas upgrading that currently constrains the wider deployment of biomethane. The work was delivered across four complementary strands of evidence: thermodynamic simulation modelling, continuous laboratory trials at the University of Southampton, a small-scale on-site demonstrator at the AD facility, and a network-level techno-economic and environmental assessment for the WWU gas network. Taken together, these strands provide a consistent and mutually reinforcing evidence base.

The simulation modelling established that there is no thermodynamic barrier to a high level of in-situ carbon dioxide conversion, and defined the safe operating window within which hydrogen is fully consumed and no residual hydrogen remains in the biogas. The laboratory trials then validated this behaviour biologically, increasing biomethane concentration from a baseline of 54% to 82% in the wheat-fed digester and 83% in the maize-fed digester (sustained over the 160-day continuous trial described in Section 3), with specific methane production rising by 55% relative to the controls. Critically, these gains were achieved without destabilising the digestion process, confirming that the uplift reflects genuine biological methanation rather than dilution or measurement artefacts. The on-site demonstrator then reproduced the effect under real-world conditions at a commercial AD site, with peak biomethane concentrations rising from a 55% baseline to between 64% and 68% at the 0.25 L/min injection rate, around 73% at 0.50 L/min, and approaching 76% at 0.75 L/min (peak values during the four-hour dosing periods described in Section 4). The demonstrator peaks remained below the sustained laboratory values, which is consistent with the short four-hour dosing duration and single-pass hydrogen supply used on site.

At the network level, the assessment indicated that, if the trial results could be achieved and maintained across all 22 biomethane plants connected to the WWU network, annual renewable gas delivery could increase from the current baseline of 1,870 GWh in the 2025/2026 regulatory year to between 2,311 GWh and 2,790 GWh. The Demonstrator 0.50 scenario is used as the near term planning case because it produced a greater methane increase than the 0.25 L/min scenario, while using hydrogen more efficiently and requiring less careful pH management than the 0.75 L/min scenario. Under this scenario, annual renewable gas delivery would increase to approximately 2,472 GWh, representing a 32.2% increase, and the number of equivalent households supplied would rise from 163,000 to approximately 215,500. The continuous laboratory scenario provides a longer term target of approximately 2,790 GWh per year, representing a 49.2% increase, if similar performance can be sustained at commercial scale. The environmental assessment found that a modelled 50% increase in output from a single 1,000 scmh plant could theoretically save approximately 4,167 tonnes of carbon dioxide equivalent emissions per year compared with natural gas, assuming complete hydrogen conversion. Lower hydrogen conversion efficiencies would increase the hydrogen requirement and reduce the carbon saving. The economic assessment found that a 50% increase in output could avoid approximately £4 million to £7.5 million of the cost of building equivalent new capacity. Financial performance varies between plants. Under the modelled assumptions, the most favourable case reaches the target return at around the assumed current hydrogen price, while other cases require lower hydrogen prices, higher gas values or greater avoided costs.

The project therefore met its success criterion: hydrogen injection into anaerobic digestion has been shown to be an effective technical solution for increasing biomethane yield, with a credible and quantified economic and environmental case for wider deployment. The approach also provides an early and practical end-use for green hydrogen at a time when direct hydrogen blending into gas networks remains constrained by regulation, while requiring no fundamental changes to existing network assets. The principal area of remaining research is the gap between the transient demonstrator peaks and the sustained laboratory concentrations, together with the hydrogen conversion efficiencies that can be achieved in practice. The demonstrator trials achieved hydrogen conversion efficiencies between 39% and 72% under single-pass dosing, whereas the laboratory achieved near-complete utilisation through hydrogen recirculation, so closing this gap is the single most important factor in determining how closely commercial operation can approach the theoretical ideal and how much hydrogen and electrolyser capacity the network will ultimately require.

The recommended next step is a follow-on NIA project to deliver the extended Phase 1 demonstration set out in Section 5.3, taking the demonstrator from short four-hour dosing periods to continuous multi-month operation with a co-located green hydrogen unit. This phase would resolve the sustained-performance and conversion-efficiency questions directly and provide the long-duration operational data needed to underpin a first commercial retrofit. In parallel, WWU should begin engaging biomethane plant operators across the network to identify suitable retrofit sites and establish a multi-party working group with Ofgem, the Health and Safety Executive, the Environment Agency, AD operators, and hydrogen suppliers to progress the regulatory and commercial framework alongside the technical work. Together these steps provide a practical, phased route from the laboratory and demonstrator evidence generated in this project to wider network deployment, delivering measurable benefits to WWU's renewable gas portfolio, its decarbonisation objectives, and its customers.