LEVIDIAN

United Utilities
Water for the North West

Department for Energy Security & Net Zero

Project Name: The Sustainable Biogas, Graphene and Hydrogen LOOP – Phase 2

DESNZ Project Number – UUW-P2

Date of Issue – March 2025

This project has been supported by the Department for Energy Security & Net Zero

Revision	Date	Description	Author	Checked	Reviewed	Approved
1.0	Jan 2025	Draft for MO Review	Various	RC		
2.0	March 2025	Final Version	Various	RC	RN	RC
3.2	June 2025	Updated final version	Various	RC		
3.3	July 2025	Final Version	Various	RC		

The Department for Energy Security and Net Zero provides dedicated leadership focused on delivering security of energy supply, ensuring properly functioning markets, greater energy efficiency and seizing the opportunities of net zero to lead the world in new green industries.

The project "*The Sustainable Biogas, Graphene and Hydrogen LOOP – Phase 2*" is part of the Department's £1 billion Net Zero Innovation Portfolio which provides funding for low-carbon technologies and systems and aims to decrease the costs of decarbonisation helping enable the UK to end its contribution to climate change.

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Abbreviations/Acronyms

ALM	Access Lifting and Maintenance
ATEX	Atmosphères Explosibles
ATO	Agreement To Operate
BECCS	Bioenergy Carbon Capture and Storage
BET	Brunauer-Emmett-Teller
BS5467	British Standard 5467 - Low voltage armoured cable
BS88	British Standard 88 - Electrical Fuses
C	Carbon
C_2H_2	Acetylene
CAPEX	Capital Expenditure
CDM	Construction (Design and Management) Regulations
CH_4	Methane
CHP	Combined Heat and Power
CO	Carbon Monoxide
COMAH	Control of Major Accident Hazards
DCS	Distributed Control System
DESNZ	Department for Energy Security and Net Zero
DSD	Descriptive System Document
DSEAR	Dangerous Substances and Explosive Atmospheres Regulations
ECC	Electric Continuity and Components

EEH	Enhanced Enzymic Hydrolysis
EU	European Union
EWW	Eric Wright Water
FCEV	Fuel Cell Electric Vehicle
FEED	Front End Engineering and Design
FOAK	First Of A Kind
FTE	Full Time Equivalent
GHG	Greenhouse Gas
GSM	Global System for Mobile communication
H&S	Health & Safety
H_2	Hydrogen
H2BECCS	Hydrogen production from bioenergy with carbon capture and storage
HAC	Hazardous Area Classification
HAZOP	Hazard and Operability
HGV	Heavy Goods Vehicle
HVAC	Heating, Ventilation and Air Conditioning
ICE	Internal Combustion Engine
IDR	Intermediate Design Review
IEC	International Electrotechnical Commission
IGEM/UP/1	Institution of Gas Engineers and Managers specification for strength testing / tightness testing / direct purging of industrial and commercial gas installations
IGEM/UP/2	Institution of Gas Engineers and Managers specification for installation pipework on industrial and commercial premises

LCOH	Levelised Cost of Hydrogen
LCRCA	Liverpool City Region Combined Authority
LJMU	Liverpool John Moores University
LOPA	Layers of Protection Analysis
MAC	Model Award Criteria
MBC	Manchester Bioresources Centre
MCC	Motor Control Centre
MENA	Middle East and North Africa
MFC	Mass Flow Controller
MO	Monitoring Officer
MoC	Management of Change
MSP	Managed Service Provider
MW	Megawatt
MWh	Megawatt hour
NWF	National Wealth Fund
O&M	Operation & Maintenance
O_2	Oxygen
OPEX	Operational Expenditure
P&ID	Piping and Instrumentation Diagram

P2	Phase 2
PCW	Person Controlling Works
PE	Population Equivalent
PRV	Pressure Reducing Valve
RACI	Responsible, Accountable, Consulted, Informed
RAMS	Risk Assessment and Methd Statement
RP	Responsible Person
SCADA	Supervisory Control And Data Acquisition
SEM	Scanning Electron Microscope
SHED	Safety and Health Electronic Documents
SIF-NZA	Strategic Innovation Fund - Net Zero Accelerator
SME	Small and medium sized enterprises
SSA	Specific Surface Area
STEM	Science, technology, engineering and maths
SV	Social Value
TGA	Thermogravimetric Analysis
THP	Thermal Hydrolysis Plant
UU	United Utilities
VPSA	Vaccum Pressure Swing Adsorption

List of units

Unit	Name	Context
°C	Degrees Centigrade	Temperature
A	Amps	Electrical current
a.u.	Arbitrary Unit	Intensity
bar	Bar	Pressure
barg	Bar	Gauge Pressure
C	Arbitrary Unit	Graphene decomposition
cm-1	Wavenumber	Spectrometry
ft	Feet	Length
g/m^3	Grams per cubic metre	Mass
$gCO_2eq/MJLHV$	Grams of carbon dioxide equivalent per megajoule (Lower Heating Values)	Emission Intensity
h	Hour	Time
kBq Co-60 eq	Kilobecquerel cobalt 60 equivalent	Ionizing Radiation
kg	kilogram	Mass
kg 1,4-DCB	kilograms 1,4-dichlorobenzene	Terrestrial Ecotoxicity
kg oil eq	Kilograms of carbon dioxide equivalent	Fossil Resource Scarcity
kg/h	Kilograms per hour	Mass
Kg/kgC	Kilograms per Kilograms of Concrete	Mass
kWh/h	Kilowatts per hour	Energy use
l	Litre	Volume
l/kgH_2	Litres per kilogram of hydrogen	HGV Diesel consumption
m	Metre	Distance
m^2/g	Squared metres per gram	Specific surface area
m^3	Cubic metres	Volume
m^3/day	Cubic metres per day	Flow
m^3/h	Cubic metres per hour	Flow
m^3/y	Cubic metres per year	Flow
mbar	Millibar	Pressure
mbarg	Millibar	Gauge Pressure
MJ/kg	Megajoules per kilogram	Specific Energy per unit of mass
MJ/m^3	Megajoules per cubic metre	Specific Energy per unit of volume
mm	Millimetre	Length
mm^2	Squared millimetre	Area
MW	Megawatt	Energy
MWh	Megawatt hour	Energy produced or used in 1 hour
nm	Nanometre	Length
Nm^3/d	Cubic nanometres per day	Flow
t/y	Tonnes per year	Production rate
V	Volts	Electrical force
Vac	Volts Alternating Current	Strength of electrical field

Executive Summary

The LOOP Phase 2 project, funded through the Department for Energy Security and Net Zero (DESNZ) Hydrogen bioenergy with carbon capture and storage (BECCS) Innovation Programme, successfully demonstrated that raw biogas from United Utilities' (UU's) wastewater treatment, can be converted into two valuable outputs using Levidian's LOOP technology: hydrogen**,** a clean alternative fuel source, and graphene, a high-value carbon material that can enhance product performance and reduce carbon footprints.

Building on laboratory-scale work completed during Phase 1 (2022), the partnership upscaled the technology to a full demonstration plant at UU's Manchester Bioresources Centre (MBC) between June 2023 and June 2025.

Originally developed using natural gas, the LOOP technology was successfully adapted for biogas containing around 60% methane, produced by anaerobic digestion within the wastewater treatment process. Biogas, drawn downstream of initial treatment through carbon filters and chillers, is processed through five identical process chambers. Within each chamber, electromagnetic waves turn methane (CH_4) into plasma and split its molecules into carbon (C) and hydrogen (H_2). The carbon is captured as graphene, while the hydrogen is purified through a Vacuum Pressure Swing Adsorption (VPSA) system.

Both outputs have strong commercial potential across various industries, offering a pathway to decarbonisation not only within the United Kingdom (UK) water industry but also wherever biogas is available — providing opportunities to replace less sustainable raw materials, secure supply chains and to transition away from traditional fuel sources.

The demonstration LOOP (LOOP100H) has successfully processed biogas up to a flowrate of 15 m^3/hr. Building on these results, further work is needed to strengthen the business case for wider deployment of LOOP systems within wastewater treatment environments:

- **Upscaling:** Development of a LOOP system (e.g. LOOP Gen2, LOOP1000) that meets the larger throughput requirements of the UK water industry.
- **Carbon Lifecycle Analysis (LCA):** Completion of a full LCA to understand the environmental impact, as Phase 2 was constrained by available operational data.
- **Commercialisation:** Growing several newly opened commercial opportunities into contracts that support decarbonisation across multiple industries.

1.0 Introduction

1.1 Consortium Information

Our project has been delivered by the following partner organisations.

United Utilities Water Ltd (Lead Partner) – 5000 employees based in Warrington, Cheshire

United Utilities (UU) is responsible for water and wastewater services in the North-West of England. Our purpose is to provide great water for a stronger, greener and healthier North-West.

Levidian Nanosystems Ltd - 80 employees based in Cambridge

Levidian is a British climate tech business on a mission to decarbonise the world's most carbon-intensive industries. Powered by its patented LOOP technology, it delivers a scalable solution that captures carbon from methane before it's burned, producing clean hydrogen and high-quality graphene — a material that enhances the performance and lowers the emissions of products in industries such as aluminium, batteries, and petrochemicals. LOOP is a modular, self-contained system that can be deployed anywhere methane is available and retrofitted to existing infrastructure. This empowers organisations to cut emissions at the source while strengthening supply chain resilience by producing critical materials locally. Revenues from hydrogen and graphene can make decarbonisation projects not only viable but profitable.

1.2 Project Background

The Department for Energy Security and Net Zero (DESNZ) has provided a total of £31 million in funding to support innovation in Hydrogen BECCS (Bioenergy with Carbon Capture and Storage) technologies. UU, in partnership with Levidian, were awarded Phase 1 funding for the Levidian LOOP technology in 2021, and were subsequently awarded Phase 2 funding in 2023. Total funding from DESNZ, for Phase 1 and Phase 2 has amounted to £3.2M.

The project expands upon the current use of the LOOP technology owned by Levidian. Levidian already use the LOOP to crack methane in natural gas into its constituent atoms, hydrogen and carbon in the form of graphene. This is done through their patented low temperature, low pressure system without the need for catalysts or additives. The Phase 1 LOOP project investigated the design and use of a LOOP for the conversion of methane to graphene and hydrogen using a fully sustainable biogas feed source from a UU sludge treatment system.

The LOOP Phase 2 project has subsequently designed and delivered a large-scale trial of the LOOP technology at Manchester Bioresources Centre (MBC). At MBC, biosolids recovered from the North West's wastewater are processed using anaerobic digestion, which breaks down the sludge to produce biogas, which is made up of mainly methane and carbon dioxide.

1.3 Aims and Objectives

Our project aims to achieve the following:

- Manufacture and installation of the largest LOOP process ever built involving the design of five process chambers
- Processing of 15 m^3/hr of biogas from the MBC anaerobic digestion system
- Capture of carbon from within the biogas at MBC
- Production of hydrogen as a discharge gas from the LOOP

1.4 Schedule and Deliverables

The Phase 2 project has been delivered between June 2023 and March 2025. During that period the project team have developed numerous physical and documentation deliverables including the implementation and operation of a LOOP100H system on site at MBC. To do this there have been multiple design deliverables such as drawings and specifications, alongside health and safety critical documents, produced to support the installation and operation. All these deliverables have been made available via the DESNZ SharePoint as evidence for completion of project milestones. Some of these deliverables are discussed in more detail in later sections of this final report.

Table 1 - Summary of Phase 2 programme and costs

	Baseline	**Actual**	
Start Date	June 2023	June 2023	No Change
Completion Date	March 2025	June 2025	Extension approved for inclusion of additional operational time following a period of downtime as a result of external factors.
Project Cost	£3.012M	£2.74M	Efficiency of £272k identified across the Phase 2 project. The project has been delivered to within 9% of the original forecast.

2.0 Engineering Design

The design of the LOOP system consists of two broad elements:

1. The LOOP100H
2. The enabling works to allow installation within the existing MBC facility

Both the above have involved detailed discussions and interactions with technical experts from UU and Levidian whilst also considering the operation and regulatory requirements of the existing processing facility.

2.1 LOOP 100H

The innovative LOOP process directly breaks down the chemical bonds of methane-based gases, such as biogas, to create hydrogen and carbon, using focussed microwaves to directly ionise the methane gas, creating a plasma. The high frequency electromagnetic microwaves energise electrons in the gas and promote collisions with other molecules, breaking them apart and generating more free electrons and positive ion radicals. This creates a cascade of reactions, which ensures a sustained plasma state while the microwave energy continues to be applied. This plasma "soup" of electrons and ions is not to be confused with plasma torches, which use plasma to create heat. In the microwave plasma method, the methane *is* the plasma, with most of the energy contained in the microwaves delivered directly to the electrons and ions of the gas. As these excited electrons and ions exit the plasma region, they cool and combine to stable compounds, principally molecular hydrogen gas and solid carbon particles in the form of graphene.

This is more energy efficient than conventional pyrolysis, since the energy needed to break the bonds is transmitted directly to the molecules. The overall system temperature remains low and there is no need to heat an entire vessel. The process also works optimally at near ambient pressures since the energy comes from the microwaves not the conditions of the system.

Microwave sources are powered by electricity, making the process portable, and zero carbon when powered by renewables. The first-generation LOOP device (capable of processing 1.5m^3/h of natural gas) was constructed at Levidian's Technology Centre in Cambridge and has been commissioned at a client site in Abu Dhabi. In its current configuration, LOOP utilises natural gas feedstock to generate graphene and a hydrogen rich exhaust gas as products. In our Hydrogen BECCS project we have developed a larger scale LOOP device (LOOP100H) with an integrated hydrogen separation module, capable of processing biogas generated from the anaerobic digestion of sludge at wastewater treatment facilities to produce high purity (>99.99%) hydrogen whilst capturing carbon in the form of graphene. The LOOP100H is designed to process up to 15m^3/h of biogas.

The LOOP100H installed at MBC can be seen below. The left-hand container houses five process chambers which perform the pyrolysis and production of hydrogen and solid carbon. The right-hand container houses hydrogen separation and graphene collection. The small compound to the right of the LOOP containers is the argon storage area used for purging of pipework for maintenance activities.

Figure 1 - LOOP100H Installation at MBC

Our demonstrator design, a diagram of which is provided in figure 2, consists of the following main subsystems: cooling, argon feed, methane feed, 5 x LOOP modules in the left-hand container and the H_2 separator and graphene collection in the right-hand container. The LOOP100H design is based on a modular system, with the basic LOOP module incorporating a process chamber with two plasma nozzles attached to it. The module also includes sensors and devices responsible for gas distribution, flow control, pressure and temperature measurements, as well as individual electrical control cabinets. This approach allows for easy and reproducible assembly of individual modules, which can then be quickly connected to each other to create bespoke systems tailored to individual client needs. The simplicity of the system, its flexibility and small size allow it to be placed in standard 40ft and 20ft shipping containers for easy transportation. This architecture allows future deployment by combining individual containers to create more powerful LOOP systems aligned to biogas availability at specific sites.

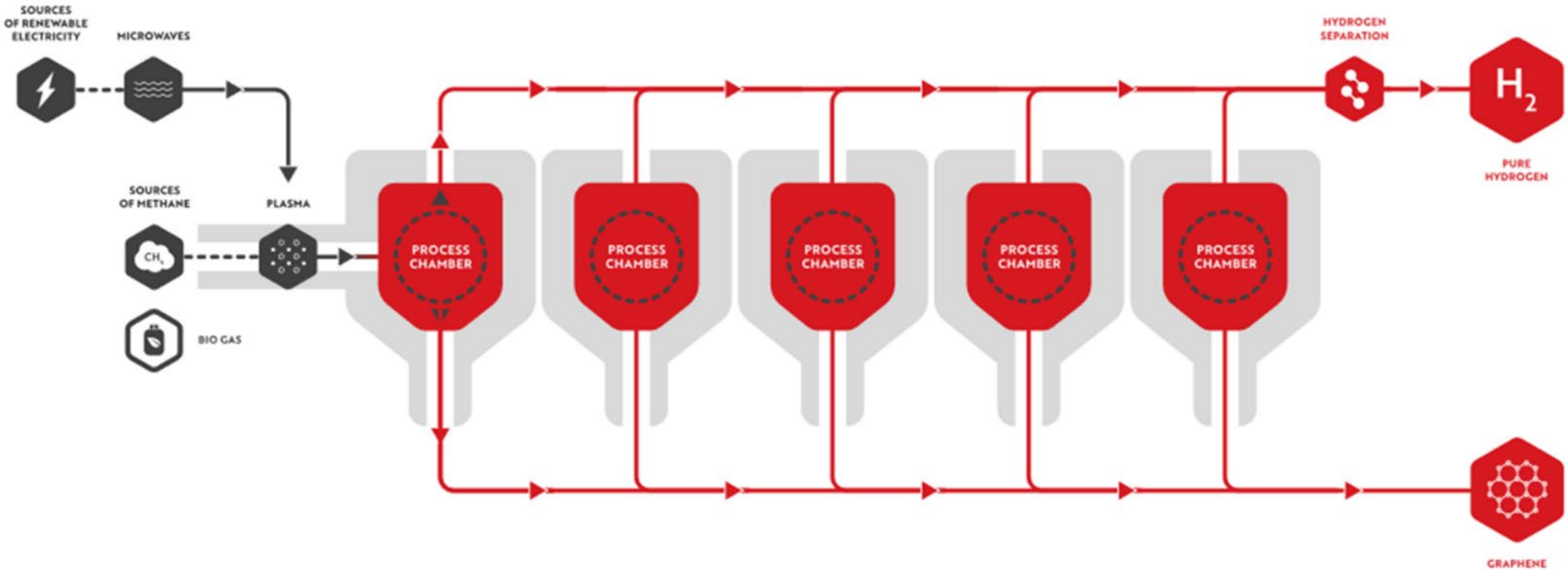


Figure 2 - LOOP100H Process Diagram

The LOOP is controlled by an industrial programmable logic controller in addition to supervision by a separate safety plc. All process data is stored in a cloud database and any faults are detected by a logic system that immediately informs the operator of a problem by sending the appropriate error code. In this case, the system automatically initiates a safe shutdown.

The graphene collection system is automated – using a vacuum system, the graphene is sucked out of the process chamber and transported to the main collection vessel. At all times, the operator has a full overview of all process parameters, the current state of the LOOP and start/stop of the LOOP. All this is possible through wireless communication, thanks to the use of Global System for Mobile Communications (GSM) modules installed inside the LOOP.

The LOOP has been designed to meet all European Union (EU) / UK certification requirements including management of explosive atmospheres. An internal safety gas system independently detects key safety parameters such as presence of hydrogen (H_2), methane (CH_4) and oxygen (O_2) in the container, status of main gas valves and pressure sensors. It is responsible for activating the emergency mode and is designed to operate in an explosive atmosphere.

Unlike other hydrogen-producing systems, LOOP does not require high pressures (the production itself takes place at pressures below 0.5 bar) and does not require any additional surfactants, catalysts, and chemicals, which significantly increases its safety. The system can operate on a start-stop basis, which means that it can be shut down almost instantly (within a few minutes) without any negative impact. The LOOP was designed for connection on site through placement on flat ground and connected to site utilities using one three-phase electrical cable, one biogas /biomethane source pipe, and one inert gas supply. The LOOP design has been optimised in such a way that over 90% of all system components are standard (off the shelf) and widely available on the market.

During the Phase 2 project, the LOOP100H design was expanded from the concept design produced during Phase 1 to the final design for manufacture. As part of this process, the Levidian design team produced Pipework and Instrumentation Diagram (P&ID), 3D models, and electrical schematics backed by underlying design schedules, calculations and information.

The detailed design included several improvements from the Phase 1 concept design, in addition to providing the detail required for manufacture:

- **Bespoke containers**
  To improve manufacturability, build time and overall cost. The bespoke solution was based on standard ISO high-cube containers modified to include insulated walls and ceiling for improved thermal management; additional lift points and access doors allowing removal of individual process chambers if required; segregated sections for input gas management panel, control panels and Heating, Ventilation and Air Conditioning (HVAC).
- **Completion of HAZOP and LOPA safety studies**
  The project team from UU and Levidian completed a detailed Hazard and Operability Study (HAZOP) and Layers of protection Analysis (LOPA) studies for the LOOP system, chaired by independent third parties. This study allowed validation of the process design and identified a number of minor changes to the P&ID which were implemented prior to manufacturing. The safety studies also formed the basis for the control system design, test documentation and system manuals ensuring the HAZOP lessons captured at each project phase.
- **Philosophy for management of explosive atmospheres**
  Management of flammable gases is the primary safety focus during LOOP design and operation. As part of the design work for the LOOP100H, we completed a ground-up review of the protection measures to prevent, detect and mitigate build-up of flammable gases. The outcome of this review included relocating inlet gas pressure regulators to a dedicated gas management panel on the outside of the container, updated Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) assessment and zoning calculations for

the container and vent locations, and specifications for all equipment located within areas which might contain flammable gases. In line with product regulations and normal practice in the UK, a third-party inspection was completed and passed at the UU site, for equipment installed in areas potentially exposed to explosive atmospheres, to ensure installation was completed in line with the updated philosophy.

- **Pressure relief via single pressure relief panel**
  To manage the risk caused by use of pressurised gases, albeit at pressures typically not exceeding 0.5barg, the LOOP includes a number of pressure relief valves. Following engagement with the site integration design team, these were routed to a single relief system supplied by Levidian as part of the container package. This approach reduced the number of vent points requiring safety review by the site team and removed an interface from the project delivery.
- **Arrangement of process chambers for ease of maintenance**
  Various adjustments were made to the layout of process chambers and container to improve accessibility for the maintenance during the trial. These included reducing the number of control components inside the process section and various component adjustments with the net effect of increasing separation on process chambers to 1900mm centres which allows consistent and safe access for personnel during maintenance cycles.
- **Update of components to accommodate anticipated water content in the biogas feed**
  During the Phase 2 design, it was identified that the potential water content of the gas feed to the LOOP would be higher than originally anticipated. In response to this, a review of all input gas components was undertaken and several items were upgraded to accept higher levels of humidity at the input gas feed. The final system was designed for any non-condensing humidity content within the biogas. It was not possible to anticipate the full impact on the plasma process until trial results were available.
- **Inclusion of real-time gas composition measurement**
  The final LOOP design included provision of a mass spectrometer which was connected to enable monitoring of input and output gas feeds from the LOOP process, in addition to hydrogen and exhaust outputs from the hydrogen separation. This inclusion allowed the visibility of gas composition for the operator and greater data resolution than was possible from gas sampling alone. However, the connection to the four gas streams did increase the complexity of the piping installation at site and would not be repeated in a mass production roll-out of the LOOP.

2.2 Manchester Bioresources Centre (MBC) Enabling Works

To incorporate LOOP into an existing biogas processing facility, we needed to understand a broad range of risks regarding technical, commercial, regulatory and environmental concerns. At the time of optioneering, UU operated 14 biogas producing and processing facilities in the North-West England. Of these facilities the MBC is the largest and provides the most appropriate technical application for LOOP on the basis that UU can provide both biogas and biomethane feed sources at the site. However, depending upon where the LOOP is located within the MBC site boundary, there are significant regulatory risks regarding explosive atmospheres and gas storage that we have needed to overcome. Through working alongside the MBC site operations team and technical experts, our LOOP project team have successfully installed the process and its supporting infrastructure in a location that mitigates these risks.

Location of LOOP at MBC

There were three locations available for the installation of LOOP at MBC as shown in the following photograph. These were as follows:

- Location 1 – Existing Crane Pad
- Location 2 – Gas to Grid Area
- Location 3 – Secondary Digesters

Figure 3 - Potential locations at MBC

By adopting our Intermediate Design Review (IDR) process and conducting a series of site visits the project team have identified the advantages and disadvantages with each location based on installation requirements from both Levidian and UU. These are shown in the table below.

Table 2 - Location selection matrix

	Location 1	Location 2	Location 3
Operational weight requires additional civil works	Existing hardstanding	Existing hardstanding	Existing hardstanding
Long supply and discharge pipe routes	Shortest	Medium risk	Longest
Access to power supply	MCC nearby	MCC nearby	MCC nearby
Location suitable for argon storage	Existing restrictions	Medium risk	Lower risk
Location suitable for purge flare	High Risk	High Risk	Lower risk
Potential for restricted access	Yes, during emergency lockdown	Yes, during emergency lockdown	Lower risk
Potential for MBC standard practices to impact on LOOP operation	Potential for shutdowns	Medium risk	Lower risk

Location 3 was selected as the LOOP location for this demonstration. This location provides us with a working area outside the more operationally intensive location of MBC and reduces potential interactions and therefore risk of impacting business as usual for UU site operations. Although pipe routes are slightly longer than for other locations, the project team agreed that this represents a suitable mitigation against the disadvantages provided by locations 1 and 2 regarding explosive atmospheres and restricted access.

Interfacing with the Existing Site

At MBC, UU produce two forms of biogas that could be used as a LOOP feedstock:

- Biogas with a ratio of ~60% methane to 40% carbon dioxide. This type of gas is produced across all UU biogas sites. The biogas passes through both chiller and carbon filtration processes to remove siloxanes and hydrogen sulphide, for use within the combined heat and power (CHP) or biogas boilers.
- At MBC, UU upgrade a portion of the biogas produced to biomethane, to produce a gas with a methane content of >95%, for injection into the natural gas grid. MBC is the only UU site that provides this level of biogas processing.

The biomethane feed source would represent LOOP being adopted in close to its normal operating environment using natural gas. Our focus has therefore been to understand how the first feed source – biogas – impacts on the LOOP processing capability, as this provides the most benefit to UU and wider biogas producing industries. The diagram below shows how the LOOP100H technology has been integrated into the MBC process.

For this trial, hydrogen was not stored, but instead it was blended back into the gas stream that feeds the CHPs at MBC.

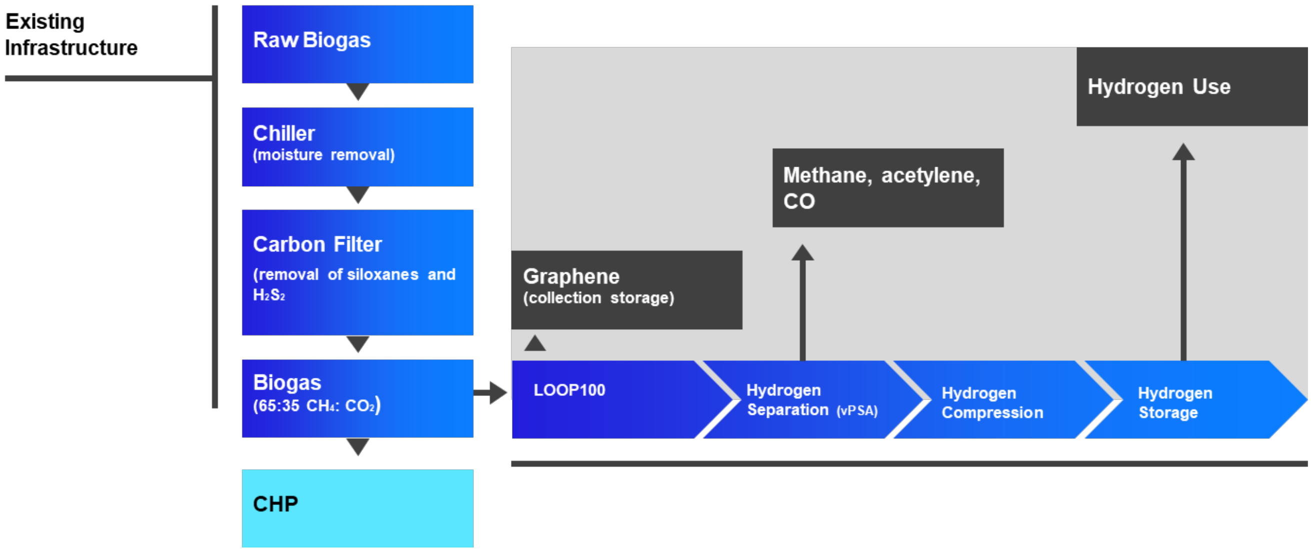


Figure 4 - Biogas Feed Process Flow Diagram

LOOP Connection Points and Pipework

Biogas Feed

With reference to the diagram in figure 4, biogas pressure is already boosted as part of the existing process at MBC. Pressure is typically 80mbarg at the source point and needed to be increased to approximately four times higher than the rest of the biogas system on site for the operation of the LOOP. This increase is still considered low pressure and allowed multiple types of pipework to be considered. UU would typically use stainless steel pipework for gas installations but, as this was a trial installed at MBC temporarily, a more suitable solution that could be removed from site efficiently was adopted. UU typically precludes polyethylene (PE) pipe for above ground gas applications due to their susceptibility to thermal expansion and lower pressure rating, but it was approved to be suitable for this specific case. This was due to:

- The short-term nature of trial, therefore lower risk from temperature fluctuation;
- PE pipe being significantly cheaper than 316L stainless steel pipe, the latter of which is typically mandated by UU for above ground applications;
- IGEM/UP/2 deeming this material acceptable in this application;
- The ease and speed of installation; and
- The pressure rating of 5.5barg, which was more than suitable for expected pressures.

Approximately 90m of 50mm internal diameter pipework was chosen for the feed line, as this matched Levidian requirements for pipework diameter, feed pressure, and feed flow rate. Due to presence of moisture usually found in biogas, a 1:40 fall was specified to allow any condensate drop out to drain back towards the biomethane plant and be captured by an existing condensate trap.

All valves in the installation were chosen using IGEM/UP/2, where ball valves of brass construction were chosen due to their ease of use, reliability in gas applications, and suitability for any pipework bore. Valves located along the main line were sized to match the pipework bore, and those acting as purge points were sized specifically to the requirements of IGEM/UP/1.

Biogas, Hydrogen and Syngas (Hydrogen / Carbon Monoxide) Discharge

The discharge section of pipework consists of three separate sources of gas, each at a maximum pressure of 480mbar:

- 99.99% hydrogen originating from the hydrogen separator via 1” (25mm) stainless steel (316L) tubing.
- Waste gas originating from the hydrogen separator, including methane, ethylene, acetylene, hydrogen sulphide, carbon monoxide, and water, via 2” (50mm) stainless steel (316L) tubing.
- Product gas from the main LOOP unit (when bypassing the hydrogen separator), containing all constituents described above, via 2” (50mm) stainless steel (316L) tubing.

All gases combine through a manifold into a ~140m long common 2” (50mm) line, eventually discharging into the main biogas line to the CHP engines immediately downstream of the gas bags, for reason detailed in section 2.2.2. The common gas line is made of Tracpipe, a semi-rigid, corrugated stainless steel pipe with a protective yellow PE cover. UU typically requires rigid 316L stainless steel pipework for above ground applications, but Tracpipe was accepted because:

- It has a maximum pressure rating of 500mbarg, ideal to cope with the maximum pressure of 480mbar to be experienced along that line;
- It is flexible, allowing long lengths to be used with minimal fittings over a challenging pipework route;
- The short-term nature of trial, therefore lower risk from temperature fluctuation; and
- The ease and speed of installation.

While PE pipe was mostly suitable for the discharge line and would have been a cheaper option, it is only rated for temperatures up to 60°C. The maximum temperature along the line is 80°C, and the Tracpipe’s limit of 95°C made this the more suitable option, rather than installing PE or rigid stainless steel pipework which would be required for a full scale installation at UU.

The LOOP produces a small amount of moisture as part of the cracking and reforming process, meaning that condensate was expected along the discharge line. Due to the terrain and existing process, condensate could not be directed to an existing trap, therefore a new condensate trap was manufactured from stainless steel and positioned at the lowest point along the line. A 1:40 fall was specified on each side to promote condensate to fall towards the trap, and the trap was sized based on pipework diameter and expected flows. The design was simplified and the financial cost reduced by removing a level probe and alarm system that is typically required by UU standards. This was replaced by a sight glass and continual operator checks of condensate level, where the risk was deemed tolerable for the duration of the trial.

Feed and Discharge Line Testing

All pipework was pressure tested by a contractor to ensure that both the feed and discharge lines met the requirements of IGEM/UP/1 for strength of pipework and leakage. Issues were identified with the documentation from an initial set of tests from a contractor, resulting in doubts from UU that the pipework had been sufficiently tested. As safety was our highest priority, retests were arranged with a different contractor prior to the LOOP becoming operational, where it was found that the discharge line had been incorrectly passed as leak free by the original contractor. Remedial work was undertaken to stop all leaks along the line followed by a retest from the original contractor, where UU Engineering acted as critical witness to ensure all work was carried out to the correct standards and procedures.

Container Base and Loading Calcs

There are 2 LOOP containers that make up the overall system: the LOOP process container and the VPSA hydrogen separator. The LOOP process container weighs 20 tonnes (40ft container) and the VPSA unit weighs 10 tonnes (20ft container). The road where the containers are located was assessed by the UU civil engineering team to ensure that it was a suitable base for the containers. The figure below shows all existing services in the area, and the LOOP containers represented by the blue and purple boxes.

The output of the civil assessment was that the containers should have no impact on buried services in the area, and that a detailed calculation was required to assess crane loading weight in the turning zone for lifting the units into place. The crane loading calculations were completed by Costain Plc, as they were the principal contractor for this part of the installation and oversaw the lifting work.

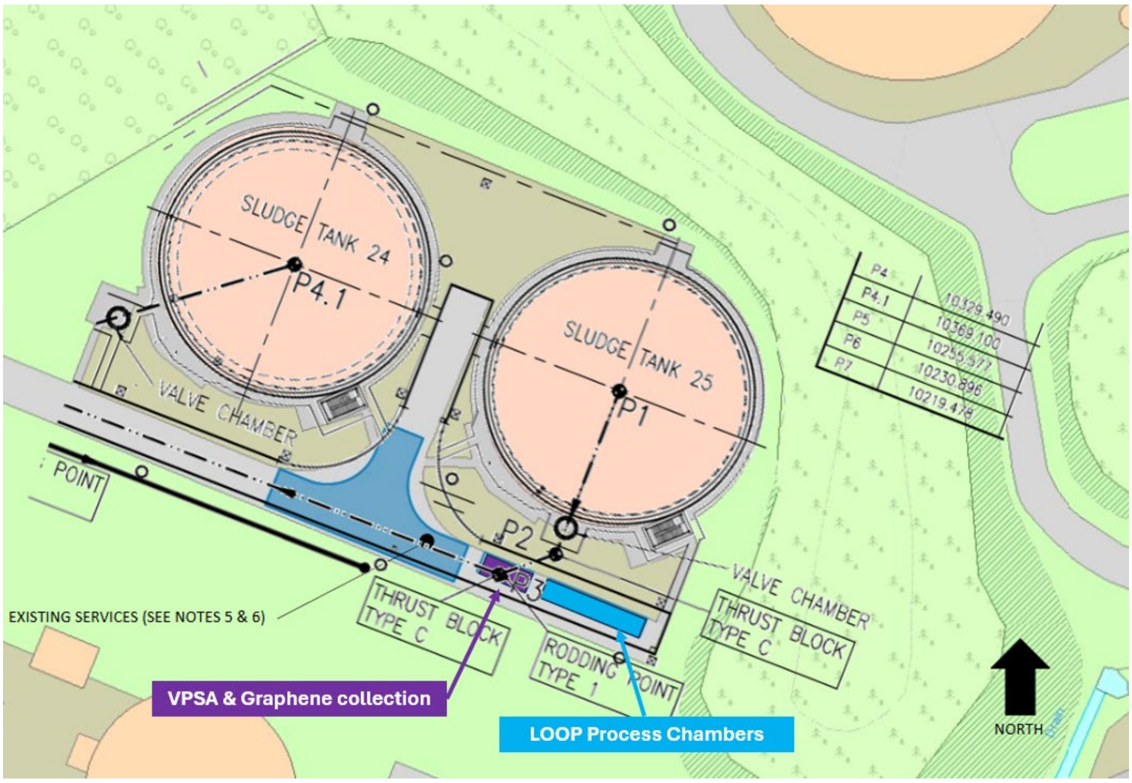


Figure 5 - Location of existing services

Additionally, the road is on a camber away from the sludge tanks, so large, re-enforced sleepers were used to level this for the containers to be placed on top of.

Argon Supply System

Inert gases are not directly involved in graphene production; however, they are used for purging the LOOP unit. In this trial, argon was used to purge the unit on every start up and shut down, which meant that a lot of argon was consumed during the trial, especially during the commissioning phase. The project team investigated the use of argon cannisters for this supply, which come in large banks. This would have required a change of the cannisters quite frequently and this made it a logistical challenge considering all site rules and working requirements. Instead, we investigated the use of a cryogenic vessel of argon on site, that would be topped up by BOC as frequently as required.

Figure 6 - Argon storage tank

The vessel that we selected was the Argon PCC950. The details of this unit are provided in the following table.

Table 3 - Argon supply system dimensions provided by supplier BOC

Equipment type	Size	Height (mm)	Width (mm)	Depth (mm)	Empty weight (kg)	Full weight (kg)	Gas	Liquid capacity (litres)	Nominal gas capacity
PCC Gas	950	2054	1200	1200	721	2045	Argon	950	784 m^3

Concrete Base and Security

A concrete base was required to be installed for the argon vessel to be located on, to ensure that the vessel had a completely flat surface to sit on. A tall fence was also required to be installed around the vessel, to ensure that no unauthorised personnel could access the argon vessel. Additionally, the vessel had to be located at least 3m from any site drains, to prevent any argon entering the drainage system.

Pipework, Valving and Control System

The argon is supplied to the LOOP unit from the cryogenic vessel via a 316L stainless steel, 1/2" (12mm) pipe. Argon is stored as a liquid in the cryogenic vessel at a pressure of 10 barg, vapourised to convert the argon to a gaseous state and provide flow and then regulated at 10 barg into the LOOP unit. The temperature of the liquefied argon is below -186°C inside the vessel. The use of trace heating on the argon supply line was initially discussed to ensure that argon temperature was high enough to meet the minimum LOOP requirement of 0°C. It was decided that this risk was small, and therefore no trace heating has been used. No issues with the argon line occurred throughout the trial.

Power Supply

The LOOP requires a 200 Amp (A) power supply as a maximum to run the equipment. This is the start-up requirement, not the normal running level once the equipment is fully operational. Based on our planned location for the LOOP, we were able to run an 80m, above ground supply cable on cable trays, from the existing MBC Gas to Grid Motor Control Centre (MCC) (UU Asset MC17-001), to the LOOP mains supply panel. A spare compartment (Compartment 8A) was within this MCC which was equipped with a 315A Fused Switch and fitted with 250A BS88 Cartridge Fuses to provide discrimination with the existing electrical equipment.

In summary, the main electrical power supply cable design parameters are as follows:

- 125A Rated Ib (Design Current) - Revised loading of 178 Amp advised by Levidian.
- Protective Device BS88 HRC
- 200A Fuse
- 80m of $95mm^2$ cable installed
- Cable is rated at 263A without any Rating Factors Applied
- Cable Specification: $95mm^2$ 4 Core XLPESWAPVC 600/1000v Rated BS5467 LSF (Low Smoke & Fire).

Costain also installed containment and cabling for the electrical, network and control cables between the two LOOP containers and the external biogas compressor. These cables enabled:

- Power supply to the VPSA and collection system
- Power supply to the biogas compressor
- Monitoring of pressure and temperature transmitters around the biogas compressor
- Monitoring of pressure, temperature and flow around the hydrogen separator and graphene collection area
- Data for plc control of the VPSA and graphene collection systems, including the associated valves.
- Safety functions including door interlocks for the graphene collection, gas detection, fire detection and emergency stops

Control Instrumentation from UU

The following signals from the LOOP unit were sent back to the MBC Supervisory Control and Data Acquisition (SCADA) system, to alert the operational team on site to any urgent issues with the LOOP. These were as follows:

- LOOP general fault alarm
- LOOP fire alarm

Training has been provided to the site team regarding what process to follow upon receiving each of these alarms. The associated procedures are in line with normal site practise, for example, a fire alarm on the LOOP would result in the site teams following the standard site procedure for a fire alarm.

Connectivity

The Levidian LOOP operations team required remote access to the LOOP control system for the duration of the trial to ensure that the system could be monitored and enable remote support for the teams at MBC. This access has been provided by connectivity within the LOOP control panel. The LOOP is a standalone system that does not require a wired or Wi-Fi internet connection from the main UU site. The access within the LOOP panel uses 4G connectivity for remote access and logging of key data points.

2.3 Health & Safety

The LOOP demonstration is a high-risk project by nature, because we are processing highly flammable substances in a pressurised system. This demonstration is also happening at MBC, a lower tier Control of Major Accidents and Hazards (COMAH) site. This means that the potential scale of impact of any incidents that happen on the project is large, and there are therefore further layers of protection that must be employed when undertaking any work on this site. This section will discuss the processes and procedures that were followed on this project to ensure that it was delivered safely at MBC.

Work Authorisation

At UU, strict work authorisation and permitting processes are used across all operational sites, for both visitor and contractors undertaking work. Anyone attending site must have a full induction, which is completed by the site operations team. All work authorisation at UU is conducted using the internal Safety and Health Electronic Documents (SHED) system. The work authorisation process enables contractors to undertake work safely on UU sites.

For each piece of work that is to be undertaken at site, the contractor must submit a set of Risk Assessment and Method Statement (RAMS) for the job. These are then reviewed by the Person Coordinating the Works (PCW) and the responsible person (RP) and checked to ensure that they are suitable for use on the site in question. Following this, a pre-start meeting is held to discuss the job and make the contractor aware of any activities happening on site that could pose additional risk within their working area. Once everyone is satisfied, the job is signed off by the PCW, the RP and the contractor, and the work can begin. The site team (RP) will also issue permits for specific types of work within a job, including hot works, working at height, digester work, etc. These are issued on the SHED system.

Additionally, different jobs will require different types of access certification. For most jobs that have a shorter duration, we will issue a single access certification, which gives the contractor access to a particular area of site, but this area remains under UU control. For larger jobs, a contractor might be given an area of site to control. In this scenario, we transfer an area over to the contractor for the duration of the job, and the contractor must then control who comes into that area, utilising their own induction and permitting processes to do so.

For this project, the work authorisation process was used for the following activities:

- Authorising Costain and Eric Wrights to undertake the enabling works installation (site transfer)
- Authorising Levidian to undertake each phase of their commissioning (single access).
- Authorising Brooke Edgley Specialist Technical Services Ltd (BEST) to undertake work to install lightening protection on the LOOP containers (single access).
- Authorising British Oxygen Company (BOC) to fill up the cryogenic argon vessel each time we need more argon (single access).
- Authorising GTS to undertake tightness testing on the gas pipework (single access).

Management of Change (MoC)

Changes on any operational sites at UU must go through a management of change process. This is an additional risk assessment that considers what change is being made, but in the context of the site. This exercise must be undertaken for every new change made with a project that is outside of the original designs, or that could have an impact on the site you are working on.

A catch-all management of change was completed for installing the LOOP units on site and operating them as per the designs provided to site. However, as the project developed, additional MoCs have been submitted to cover changes to the designs and operation, including:

- Removal of 3 x flame arrestors from the LOOP process unit. This was due to an issue arising with pressure build up and the unit was tripping out consistently. The removal of the flame arrestors was assessed as creating no additional risks on the system.

- Changing the size of one of the VPSA outlet pipes from 1” (25mm) to 2” (50mm) pipework, to mitigate a pressure issue that was causing the unit to trip out.

CDM

Construction Design Management (CDM) regulations are pivotal to any project and are there to ensure that projects can be delivered safely. For this project, UU undertook the role of Principal Designer, and Costain undertook the role of Principal Contractor when required – this was mainly during the initial construction phase. Once Costain had finished the enabling works and left site, there was no longer a requirement for a Principal Contractor. Careful consideration had to be made during the LOOP commissioning phase to ensure that there were not multiple construction activities happening at the same time on site.

Agreement to Operate (ATO)

At UU, we utilise a process called the Agreement To Operate (ATO) to handover equipment to operations once it has been commissioned. In normal operation, a contractor might replace some equipment on site or install a new process. The contractor would then provide a suite of documentation to the site operations team covering how the kit was installed, commissioned and tested to adhere to relevant standards, as well as any relevant training on how to use and operate the new equipment. Following this, the equipment would be handed back to operations to manage, and an ATO would be assigned to complete this handover.

For innovation projects, this process must be adapted to suit to different ways of working that we use. Due to the temporary nature of innovation trials, we may not ever fully hand over something to operations, and we may want to utilise the supplier to operate the kit while it is on site. Additionally, we have multiple parties involved as usually we engage a contractor to connect the innovative equipment to UU equipment. This means that there is a requirement for a multi-party ATO between UU Operations, UU Engineering, the supplier of the innovative kit (Levidian) and the lead contractor (Costain Plc).

To move through the ATO process efficiently, a UU asset integration engineer was brought onto the project to support. The role of the asset integration engineer is to support the team and ensure that all required evidence is provided by relevant parties to enable sign off. For this project, there was a large range of documentation required for asset handover, this included:

- Defects and SHE inspection reports
- All relevant RAMS (as described in the work authorisation section above)
- Electrical test certificates
- Gas pipework strength and tightness testing certificates
- HAZOP and Access Lifting and Maintenance (ALM) documentation
- Lifting equipment inspection sheets
- Critical witness testing certificates
- Pre-commissioning documentation
- DSEAR Risk Assessments and EX rated equipment inspection certificates
- Training documentation

The Interim ATO was successfully signed off before biogas was introduced into the LOOP100H system in December 2024.

H&S Reporting and RACI Matrix

To ensure that roles and responsibilities were very clear, the RACI matrix on the next page was developed for use on the project. This sets out who is ultimately responsible and accountable for different tasks, such as site inductions, reporting incidents and LOOP operation. It also sets out who must be consulted regarding certain tasks and who must be kept informed.

Table 4 - Responsible, Accountable, Consulted, Informed (RACI) matrix

LOOP Operation RACI	Project Manager	Programme Manager	Process Scientist	Process Engineer	Mechanical Engineer	Production Engineer	Process Controller	Treatment deliveyr Manag	Chief Engineer	Bioresources & Green Energy Director	Head of Bioresources & Bioenergy Operations	Head of Strategy and Commercial Services	Head of Engineering	Process Safety Business Partner	Head of Process Safety	Project H&S Manager	Project Delivery Manager	Process Control Engineer	Project Manager	LOOP Technician
Task																				
Site inductions & briefings	C	I	I			R	I	A									C	C	C	C
Work authorisation	C	I	I			R	I	A									C	C	C	C
Site safety management (within pilot area)	A	C	R			C	I	I								C	C	C	C	C
LOOP commissioning & functional testing	I	I	I	I	I	C	I	I	I								A	R	I	C
LOOP Operation	I	I	I	I	I	C	I	I	I								A	C	I	C
LOOP Maintenance	I	I	I	I	I	C	I	I	I								A	C	I	C
Making process changes that interface with MBC	C	I	I	C	C	A	C	C									C	R	I	C
Making process changes to LOOP	C	C	C	C	C	C	C	I	I								A	R	I	I
Recording of Management of Change in SHED	C	C	I	C	C	R	C	A	I							C	C	C		C
Reporting Incidents	A	R	R	R	R	R	R	R	R	I	I	I	I	I	I	I	R	R	R	R
Raising airlines	A	R	R	R	R	R	R	R	R	I	I	I	I	I	I	I	R	R	R	R
Investigating airlines	C	C	C	C	C	C	C	A	R	I	I	I	I	C	C	C	C	C	C	C

2.4 Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) and Hazardous Area Classification (HAC)

As the trial involved the handling and production of dangerous substances such as methane and hydrogen, UU are legally required to meet DSEAR. Hundreds of UU sites store or handle dangerous substances and/or contain explosive atmospheres, therefore UU have a specific set of guidelines and documentation that must be completed to the satisfaction of our DSEAR team for processes to be installed and operated. On larger scale construction projects, all our design and construction partners will understand these requirements and be well versed in how to adhere to them. Specific individuals will also hold the required competencies for design, installation and inspection of Ex-rated equipment. When working with non-framework suppliers such as Levidian, additional due diligence must be undertaken to understand the competency of the organisation and the individuals undertaking work on the project. In some cases, additional checks and measures will be implemented to provide assurance to the UU DSEAR team regarding the safety of the new process to be installed.

DSEAR Risk Assessments & HAC Drawings

For this project, 2 DSEAR risk assessments have been completed. This is not standard practise, but it was the best way to tackle the assessment for this project due to the containerised nature of the LOOP units. For future projects, Levidian would work with one of UUs DSEAR consultants to generate a standalone DSEAR risk assessment for a new installation. Site DSEAR risk assessments would also be updated for a permanent installation. Levidian undertook a DSEAR risk assessment for the LOOP units that they supplied for the project. AtkinsRealis UK Ltd undertook a risk assessment for the enabling works element of the project. This covered the elements that were designed by UU and installed by Costain, including the biogas feed line, discharge lines, power supply cable and the argon supply line.

When a DSEAR assessment report is produced, a HAC drawing is also typically produced as best practice. This shows a diagram of the equipment being installed, its location on site, and the different zones that are present when gas is running through the system. These diagrams provide a quick and easy way for those visiting to site to understand where there are DSEAR zones in an area, giving clear guidance on areas where caution should be taken e.g. exclusion of mobile phones, hot works, etc.

Ex-rated Equipment

For each piece of equipment detailed in the Ex-register (UU Document AST1006) the following should be submitted to UU for approval by the DSEAR team. In addition to this, any other verification documentation deemed necessary by the UU DSEAR team, e.g., manufacturing information / calibration certificates / preservation / etc will also be requested. This may be dependent on the work being completed or type of equipment installed.

- Separate Ex Inspection sheet (including defect/non-compliance list if categorised for a repair requirement). Inspection sheet should have equipment grid location from the associated site hazardous area classification drawing).
- ATEX certificate
- Descriptive System Document (DSD)
- I.S circuit loop calculations (where applicable)
- I.S circuit loop drawing (where applicable)

For this project, Levidian submitted a full suite of certification for the Ex rated equipment installed in the LOOP units. A full inspection of all Ex-rated equipment was undertaken by Vaporline in August 2024. The following 2 issues arose during this process but were managed effectively to ensure that the installation could be progressed.

- Levidian designer was not certified to CompEx-12 and therefore additional checks were undertaken on the descriptive system document calculations by Z-Tech, an approved firm that UU frequently uses to complete DSEAR calculations and undertake inspections.

- During the COMPEX inspection by Vaporline, a detailed review of the installed electrical equipment and system, it was found that one of the Levidian control panels did not have sufficient segregation between Ex i and Ex e equipment, which are 2 separate special conditions applied to pieces of rated equipment. Levidian had to rearrange the panel and supply a second panel to provide suitable segregation between Ex i and Ex e equipment.

All relevant documentation was submitted to and checked by UU prior to biogas being run through the unit. This formed one part of the ATO put in place been UU Operations, Costain and Levidian.

2.5 Commissioning

Enabling Works Mechanical and Electrical Commissioning

Costain Plc undertook the installation and commissioning of the LOOP enabling works. The following commissioning activities were undertaken by Costain and other contractors.

Electrical Testing

Costain supplied and installed the main power cable to the LOOP unit, as well as the interconnecting cables between the two LOOP units, and the cables required for sending signals back to the MBC site SCADA (online monitoring system).

The mains power supply cable was calculated using an approved cable sizing software to determine the required cable size. The calculation stated a $95mm^2$ 4 Core Cable (TP&N) was required for this power supply. A separate earth cable of $95mm^2$ was also required to maintain earth continuity

Following the installation of the power feed cable the following tests were completed to ensure the safety of the power supply

- Earth continuity & earth loop impedance tests
- Insulation resistance tests

The interconnecting control cables are used to carry signals between each unit and the voltage applied is less than 110Vac. The only required test for this cable(s) was continuity testing and insulation testing. The cable would not be subject to mains voltage hence no Electric Continuity and Components (ECC) testing as per the above tests.

Tightness Testing

All feed, discharge and interconnecting pipework was tightness tested once installed to ensure that no gas could leak out.

Table 5 shows the different tightness tests carried out. Certification was submitted as part of site acceptance testing.

Table 5 - Pressure testing results

Name	Pressurisation Point	Test Pressure (barg)	Pass/Fail
Chamber X (x5) Hopper to Purge Exhaust Manifold	Connection to X.RV2 (Pressure Reducing Valve (PRV) removed)	0.53 Barg	Pass
Chamber X (x5) Product Gas to VPSA Bypass, H_2 Separator, and Mass Spec	X.PL601 (downstream of X.RV1 PRV)	1 Barg	Pass
Methane Gas Panel to Mass Spec	Connection to Y.RV2 (PRV removed)	1 Barg	Pass
H_2 Separator to H_2 Outlet, Waste Gas Outlet, and Mass Spec	Connection to V10-LOOP purge point	1 Barg	Pass

LOOP 100H Commissioning

As a First of a Kind (FOAK) product, installed in a high-hazard environment, the commissioning process was planned to include an extended period of checks and tests. Pre-commissioning and commissioning procedures and risk assessments were submitted by Levidian to UU for review and entry into the site safety management system. Following commissioning, the project used a harmonisation period to identify unforeseen issues and increase the utilisation of the LOOP.

Pre-Commissioning

A small number of manufacturing activities were transferred from LOOP build in Cambridge to site to allow completion of build to be undertaken in parallel with the site installation activities. Final build activities included installation of mass flow controllers which were delayed in delivery, completion of labelling and tagging, and piping installation around the collection system.

A build inspection was completed which included walk-down of the P&ID, visual checks on electrical and mechanical connections, confirmation of availability of pressure test and installation certificates from site installation and LOOP testing in Cambridge, and inspection for compliance to International Electrotechnical Commission (IEC) 60079 by an independent COMPEX inspector.

LOOP electrical power on was completed by Levidian engineers with support from UU's site and electrical engineering team. Initially the feed to the LOOP was energised, followed by a staged energisation of each LOOP sub-system, with each system shown to be working before the next was energised. The LOOP comprises 8 control panels which were energised in turn, with 24V control supplies and sub-devices energised once panel energisations were shown to be healthy. Once the LOOP was fully energised, the LOOP feeder remained powered throughout commissioning, with isolation of LOOP for commissioning requirements controlled by Levidian.

The LOOP includes fluids in the form of mineral oil for outlet gas filtration and water/glycol mixture for process cooling. Once fluids were installed, levels were checked, and the cooling circuits were bled of air and flows balanced across the various cooled components using needle valves included in the circuits for that purpose.

Control and safety plc software was loaded, using configuration files which had been developed and tested using simulators. Once control software was loaded, instruments deemed process critical or required for data collection were calibrated, specifically:

- Oxygen, flammable and hydrogen sulphide gas detection
- Pressure sensors installed for safety reasons
- Temperature sensors installed for safety reasons

- Mass flow meters for inert and flammable gases
- Mass spectrometer for gas composition measurement
- Load cell for carbon quantity measurement

Commissioning

The aim of the commissioning phase was to take the LOOP and site installation, which was practically complete, and demonstrate safe production of hydrogen and graphene. During commissioning, daily meetings were held between Levidian and UU staff. Meetings included site and office-based teams with the aim of ensuring timely closure of completion, coordination of multiple parties at site, and tracking of snags and learning.

Argon was introduced to the LOOP in stages starting at the cryogenic storage tank, followed by the LOOP main inlet pressure regulator and control valves then each subsequent process step in the LOOP system. At each stage, pressure stability was checked and joints were tested for leaks using leak fluid. Once argon flow control and pressure hold was demonstrated at each section of the LOOP, argon was used to complete an additional pressure hold and tightness test. Argon was used to purge the biogas compressor, inlet, process and outlet pipework to the LOOP system tie in points, ensuring no flow of air could be introduced to the MBC site.

Safety system validation was completed following introduction of argon. Validation followed procedures set out by the relevant functional safety standards (ISO 13849-1) in which each identified safety function was tested, end to end, to prove the system operation prior to use. Validation testing was completed following introduction of argon because it allowed more realistic testing of purge proving and over-pressure protection.

Plasma testing was completed initially using argon. Argon gas was flowed through each nozzle individually and a plasma ignited. Once ignition was achieved, the microwave tuning components were adjusted until a stable plasma was seen with minimal reflected power observed at the magnetron head. Biogas was then introduced to the system following the same staged process as used for introduction of inert gases.

Plasma testing using biogas was initially completed manually, igniting a plasma at each nozzle and further tuning the microwave system to minimise reflected power on biogas. Key learning from this stage of commissioning was that the LOOP can ignite and sustain plasma directly on biogas.

3.0 System Cost Estimates

The overall cost for delivery of our demonstration project at MBC was £2.74M. However, we still believe our initial estimate of £3.012M is more aligned to the requirements of a full-scale installation of a LOOP100H system and the £2.74M figure should not be considered as a guide cost. This is due to the factors discussed in more detail in Section 3.2 below, including the need to provide suitable hardstanding – we were fortunate to find an appropriate location at MBC for the demonstration – and the requirement for stainless steel biogas pipework, as our temporary pipework would not be approved for permanent installations. Our assessment would also need to be increased to allow for upscaling of the LOOP process and, depending on the chosen location, the number of LOOP process units to be installed. This final point regarding the number of units would also influence the civil, electrical and mechanical scope within the enabling works package.

3.1 LOOP100H System

Supported by the Hydrogen BECCS Innovation Programme, the LOOP technology has undergone advancements, improving efficiency, reducing operational costs, and enhancing production capabilities. Our phase 2 project has seen the LOOP progress from a Technology Readiness Level (TRL) of 5, laboratory testing of integrated/semi-integrated system, to 7, integrated pilot system demonstrated, with regard to the use of biogas a feed substrate. The continuous innovation of the 2nd generation LOOP shows major improvements in energy efficiency, production output, carbon capture, and cost reduction.

The cost to build LOOP10 was £0.5M as a proven, small-scale system. With the development of LOOP100H, costs increased to circa £2.0M due to its larger multi-nozzle system. Total direct cost for the LOOP100H delivered to UU has been £1.3M of which an estimated 20% could be avoided in future builds due to learning and improvements in design, procurement and supply chain.

LOOP Gen2 maintains a cost of £2.0M, reflecting cost efficiencies achievements through the improved nozzle and optimised performance. These improvements are attributed to the combined improved optimisation and cost of using larger equipment of the LOOP Gen2.

Operational and maintenance costs followed a similar trend. LOOP10 required £0.1M per annum for basic maintenance. Extrapolating the costs for the LOOP100H at UU and combining with known replacement intervals allows us an estimate of £0.2M per annum for LOOP100H as the system scaled and improved in reliability. With LOOP Gen2, Operation & Maintenance (O&M) cost estimates rose slightly to £0.27M per annum to accommodate O&M cost of the multiple units. While capital costs increased significantly from LOOP10 to LOOP100H, the investment stabilises with a singular nozzle Gen2 module. The O&M costs remain controlled despite enhanced capabilities.

The cost build-up analysis highlights the efficiency improvements and cost reductions achieved through technological advancements. Despite initial capital expenditure increases, LOOP Gen2 delivers improved performance, higher output, and lower operational costs, making it a financially viable solution for large-scale deployment.

3.2 LOOP, Enabling Works and Operations budgets for Phase 2

The enabling works package was delivered by the UU (UU) Managed Service Provider (MSP) Costain. This is an existing framework agreement that enables the procurement of services that fall outside of the skill, knowledge, experience or training of our operators up to a value of £4M.

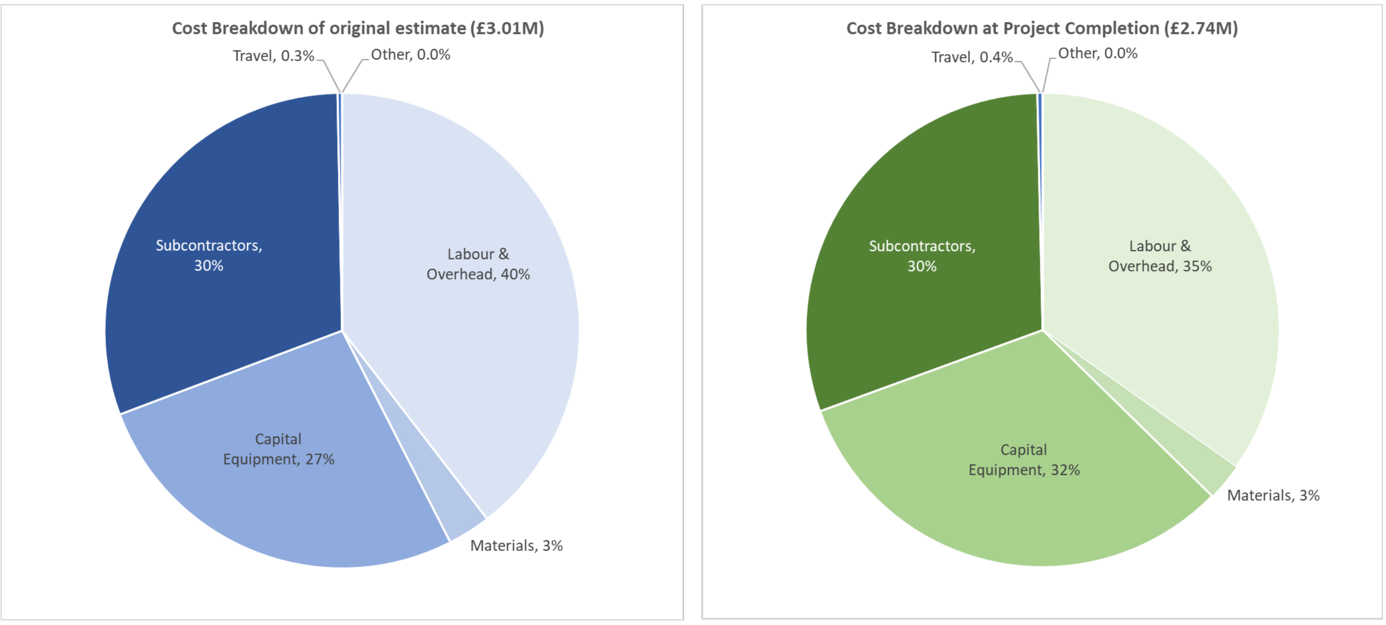


Figure 7 - Cost breakdown

Our original estimated cost for enabling works on the LOOP project was based on actuals we had incurred on previous innovation projects. This included the need for the provision of surfaces that were free draining to a point where water could be returned to the inlet of the wastewater treatment plant and suitable pipework for the safe transfer of biogas to and from the LOOP system. There was also the requirement to provide interconnecting pipework between the two LOOP containers and a power supply for operation.

For operation of the LOOP, we included the input of a Process Scientist with the support from the UU Engineering Team, MBC Site Operations and Levidian.

A breakdown of the original estimated cost and resultant outturn cost are provided below. Although the total amount of money spent in delivery of the LOOP project is less than envisaged at proposal stage the breakdown between types of expenditure has remained similar.

- Labour and overhead costs were less than expected due to the reduced operational period for the LOOP based on the required reporting period (to end of March 2025) rather than the end of the trial period (May 2025). This has been a result of the increased time we required to understand installation, make the required alterations to pipework and adapt the LOOP process to the use of biogas as a feed substrate. This has all led to us not requiring as much time from our Process Scientist and also a reduction in the time spent by Project Management resources. At UU we have seen a reduction of almost 40% compared to what we envisaged as the required man hours input over the project. The opposite has been seen at Levidian where a small increase in the amount of funding used on man hours has been seen. This is due to the increased level of site attendance required during installation and commissioning at MBC. This is also reflected in the small increase in travel expenditure.

- Capital equipment costs have risen across the delivery period due to the need for more suitable mass flow controllers (MFCs). Sampling and analysis of the feed biogas, which showed moisture content in excess of the specified levels for the original MFCs, led to a design decision to exchange the parts for more suitable units. This was completed and costs absorbed within the project funding without the requirement to uplift the overall budget.

- The proportion of budget spent on subcontractors remained the same (30%) between the proposal estimate and final outcome. However, the subcontractors used by the project team have changed due to the requirements of this biogas processing project.

Table 6 - Difference between demonstration cost categories

Subcontract	**Original Budget**	**Actual Spend**
Enabling Works (Costain)	£502,000	£343,077
DSEAR (Atkins)	£20,000	£21,928
LOOP HAZOP (Risktec)	£0	£18,106
Carbon (Jacobs)	£70,000	£70,000
Social Value (Jacobs)	£47,000	£47,000
Commercialisation (Jacobs)	£57,900	£62,957
Regional Commercialisation (LJMU)	£119,990	£118,986

As the project developed, we identified some safety critical elements that required the input of specialist consultancy. This has resulted in the increase to the DSEAR and HAZOP input shown above. HAZOPs within UU related to enabling works can be completed by in house resources, however, the LOOP required the knowledge and experience of a consultant that had completed reviews on previous versions of the process. Risktec were therefore engaged on the project having worked alongside Levidian on detailed HAZOPs in the past. This approach has provided both Levidian and UU with greater certainty of safe operation for future LOOP systems.

- Some elements of our Phase 2 scope have been influenced by the amount of available time for operation as we approached the end of the project period. As mentioned above Process Scientist time has been significantly reduced. This has also been the case for sampling and analysis of biogas and discharge gases. The amount of time spent completing scheduled and non-scheduled maintenance during the operational period has reduced the requirement for sampling of all gas streams.

3.2 Levelised Cost of Hydrogen (LCOH)

Initial LCOH Calculation – Phase 1 Results

During the initial bid submission phase, Jacobs developed a model to estimate the Levelized Cost of Hydrogen (LCOH) to evaluate the economic viability and environmental profile of LOOP. This estimate was derived from the hydrogen production rate using the LOOP10 system and projected LOOP1000, scaled up to a LOOP5000 configuration. The assumptions used in this calculation included:

- The model was based on a LOOP10 and estimated LOOP1000 system with a biohydrogen production rate of 20 kg/h, which was scaled up to a LOOP5000 system with an assumed biohydrogen production rate of 100 kg/h.
- The initial calculation did not account for yield impact of hydrogen separation.
- The estimated LCOH was £62.9/MWh H_2, compared against a baseline reference £87.8/MWh H_2 for a Waste Gasifier with CCUS (48 MW) over a 20 year project lifetime as shown in the two graphs below.
- The bid submission was based on projections for a Phase 2 + 5 years scenario.

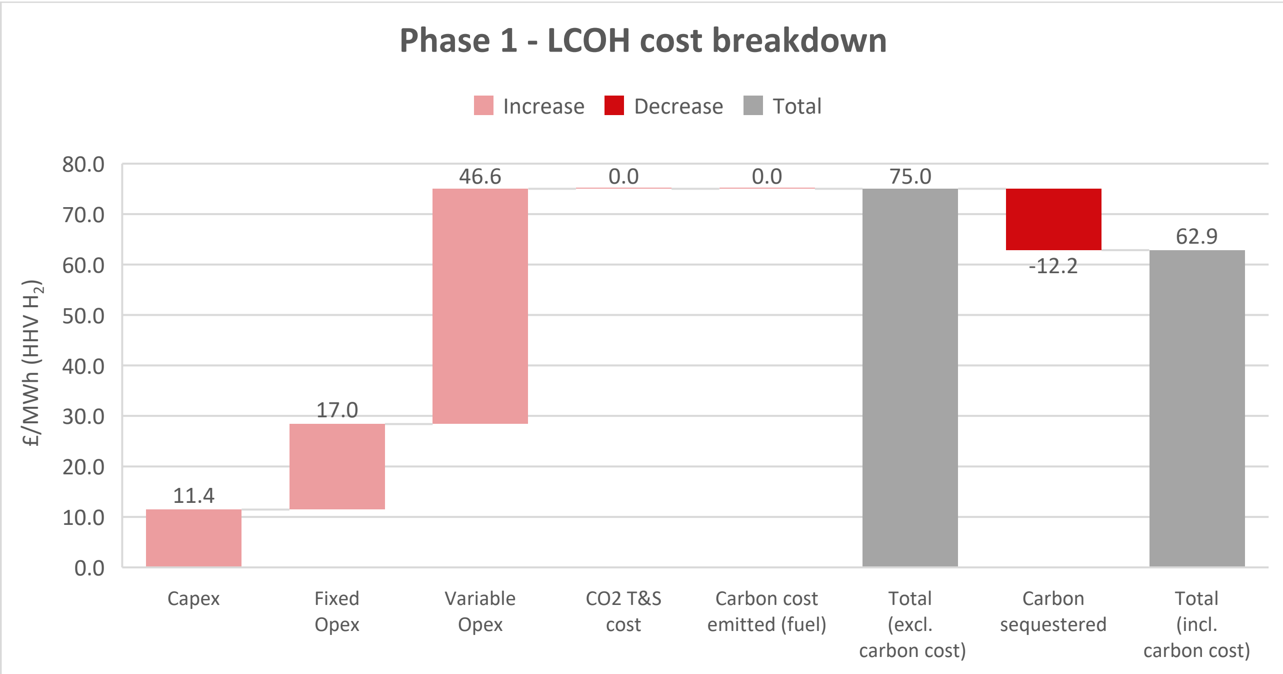


Figure 8 - Phase 1 LCOH Estimate for LOOP5000

Adjusted Hydrogen Production: The model recalculated the expected annual biohydrogen production, estimating a maximum output of 781 tonnes per year (t/y) for a LOOP5000 and 74.6 tonnes per year for a LOOP1000. Based on 5 nozzles producing 2kg/h for a LOOP1000 and 25 nozzles producing 4kg/h for LOOP5000 with an increase in system availability.

Updated LCOH Calculation – Phase 2 Results

As part of the Phase 2 project, Jacobs revised the LCOH model to incorporate updated assumptions and a more accurate representation of system performance. The key updates included:

- **Incorporated Hydrogen Yield Losses:** Unlike the initial bid submission, this model accounts for hydrogen yield losses due to purification of LOOP output gases to fuel cell grade hydrogen.

- **Operational Life Assumption:** The updated model assumes a 20 year operational life instead of the previous 25 year assumption. Hydrogen infrastructure projects typically adopt a 20-25 year lifespan for financial modelling, aligning with depreciation schedules and investment recovery periods.
- **Updated Capital Expenditure (CAPEX) & Operational Expenditure (OPEX) Estimates:** The finance team provided capital and operational expenditure figures, excluding margin. With a refined operational life, CAPEX and OPEX were adjusted to reflect more accurate capital recovery and depreciation rates, leading to a lower projected LCOH.

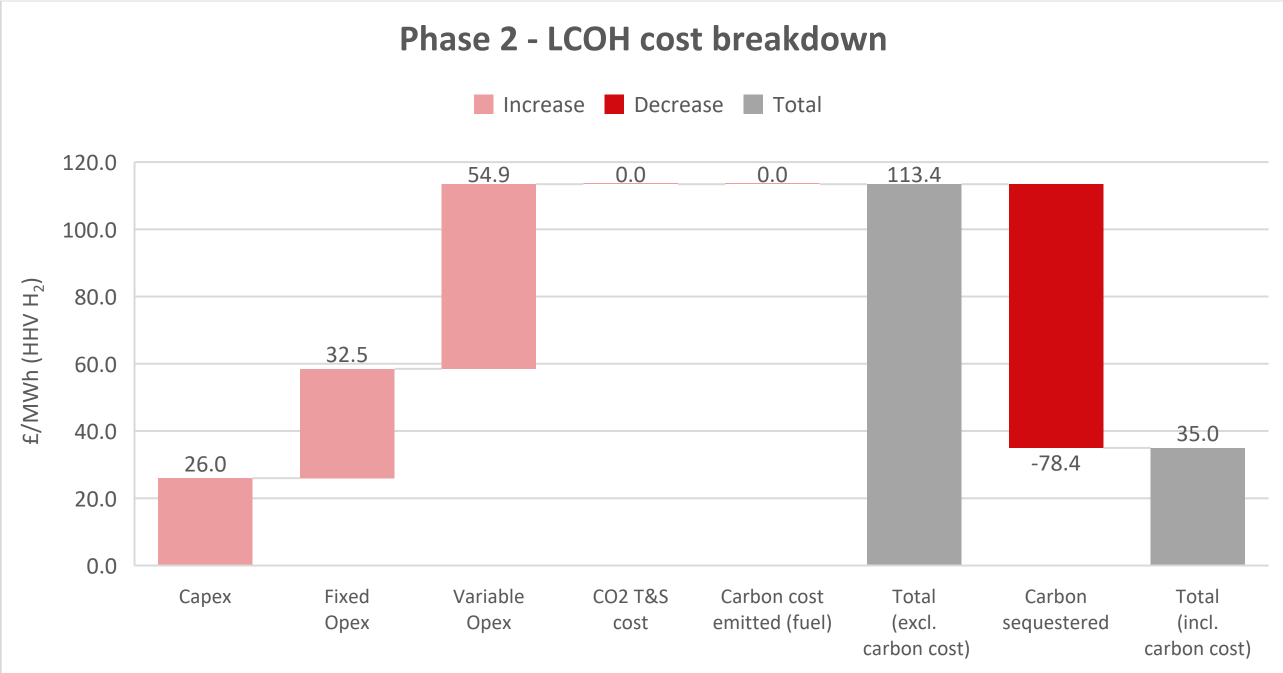


Figure 9 - Phase 2 LCOH cost breakdown

The revised model produced an LCOH estimate of £35/MWh H_2, significantly lower than the initial bid submission estimate and baseline reference. This substantial reduction is attributed to improved system efficiencies leading to increased carbon sequestration despite increased estimates for capital and operational costs.

4.0 Demonstration and Testing Results

It is important to note that the following results are based specifically on outputs from a biogas source.

4.1 Graphene Production

Carbon powder samples were periodically taken from the LOOP and analysed using various techniques including: Raman spectroscopy (Raman), thermogravimetric analysis (TGA), Brunauer-Emmett-Teller (BET) analysis, scanning electron microscopy (SEM), and bulk density. The various methods provide different analysis to confirm graphene composition, structure and crystallography.

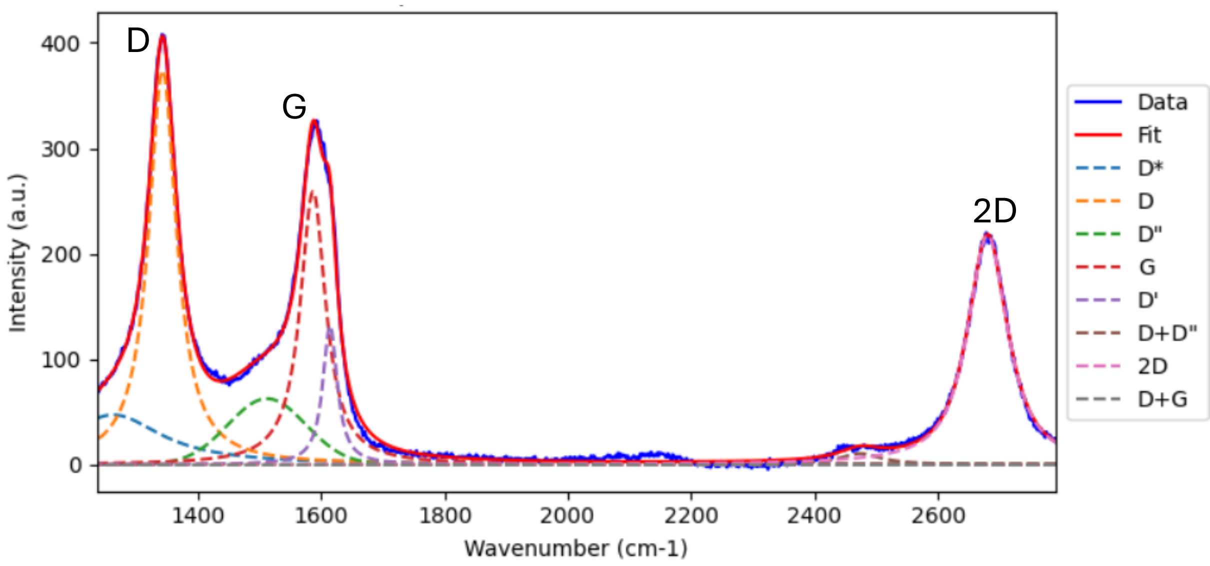


Figure 10 - Raman spectral decomposition

Raman spectral decomposition shown in Figure 11 measures distinct peaks which allow measurement of graphene structure based on the relative size of the 'G', 'D' and '2D' components of the measured data. UU LOOP samples exhibit the three prominent peaks expected of graphitic carbon, namely the D, G, and 2D. The G peak is always present with sp2 (graphitic) carbon. The D peak is present when the sp2 structure is disordered and/or many edges are present due to small particle sizes. The 2D peak is indicative of long-range order (crystallinity). For example, the 2D band is not present or is highly suppressed for highly amorphous sp2 carbon, such as carbon black, but begins to appear as layers of sp2 carbon begin to stack. The singular peak feature of the 2D band indicates turbostratic (random) alignment between the stacked layers.

TGA

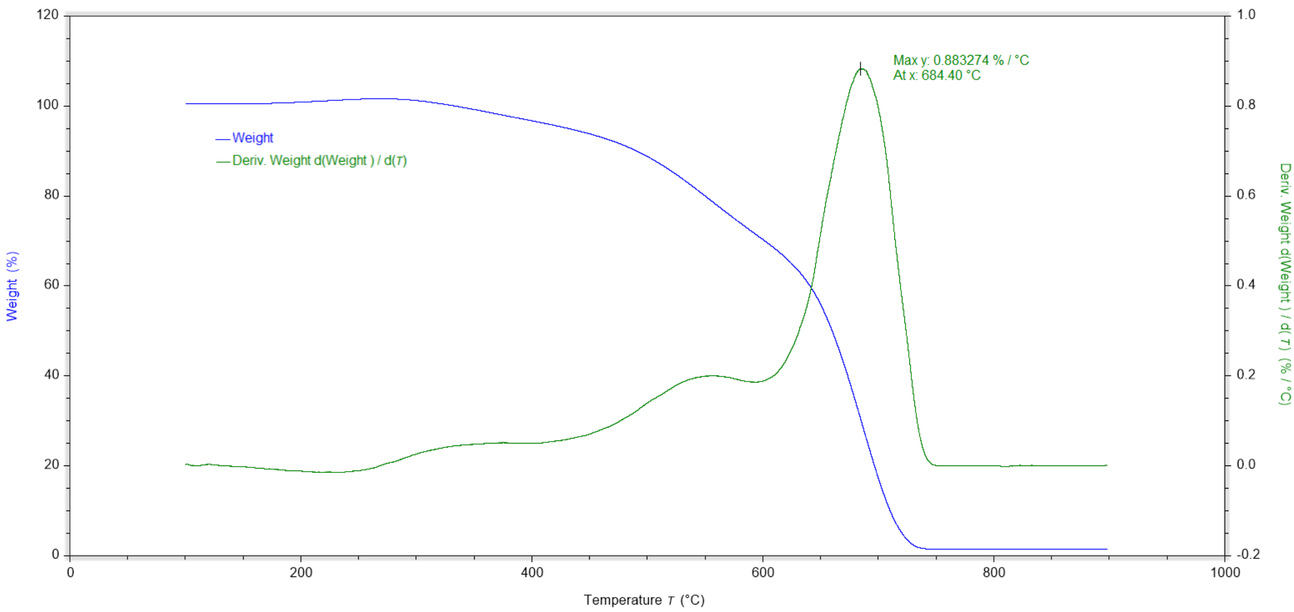


Figure 11 - TGA Decomposition Peaks of Graphene Produced at UU

Samples were treated in a TGA at a temperature ramp rate of 10 °C/min from room temperature to 900 °C under continuous air flow.

The carbon samples show several mass loss peaks below 600 °C, with a primary loss peak at ~685 °C. Below 400 °C, mass loss is attributed to the presence of hydrocarbons which become volatile and may leave behind amorphous residue. Mass loss between 400-600 °C is typically attributed to oxidation and decomposition of highly disordered/ contaminated/ amorphous carbon, whereas >600 ºC decomposition is related to increasingly ordered, higher purity carbon structures such as graphitic carbon. Mass loss of ~30% at 600 ºC indicates a significant fraction of the collected material is not graphitic carbon, but rather a mixture of hydrocarbons bonded and/or adsorbed to the surface of the solid carbon structure.

BET

BET is used to measure a materials Specific Surface Area (SSA), which is the amount of surface per gram of material and is often expressed in terms of m^2/g. Here, a 5-point nitrogen BET method was used to determine the SSA of carbon samples. In general, for a graphitic carbon to be considered graphene-like it will exhibit a SSA >100 m^2/g, going as high as ~2600 in the case of single layer graphene, since the SSA will reflect the number of layers present in the graphitic structure. Measurements from these samples show an average SSA of ~309 m^2/g. Furthermore, some of the material was treated in the TGA to burn off the hydrocarbons present on the surface to expose the underlying carbon surface. The surface cleaned samples exhibit a significantly higher SSA of ~850 m^2/g, correlating to an average of ~3 layers in the graphitic carbon structure.

SEM

SEM imaging (below) reveals a highly porous network structure at the micro and nano scale. The individual particulates range in size from a few 10s of nanometers up to a few 100s of nanometers. These primary particles also have a mixture of spheroidal and flake like geometry.

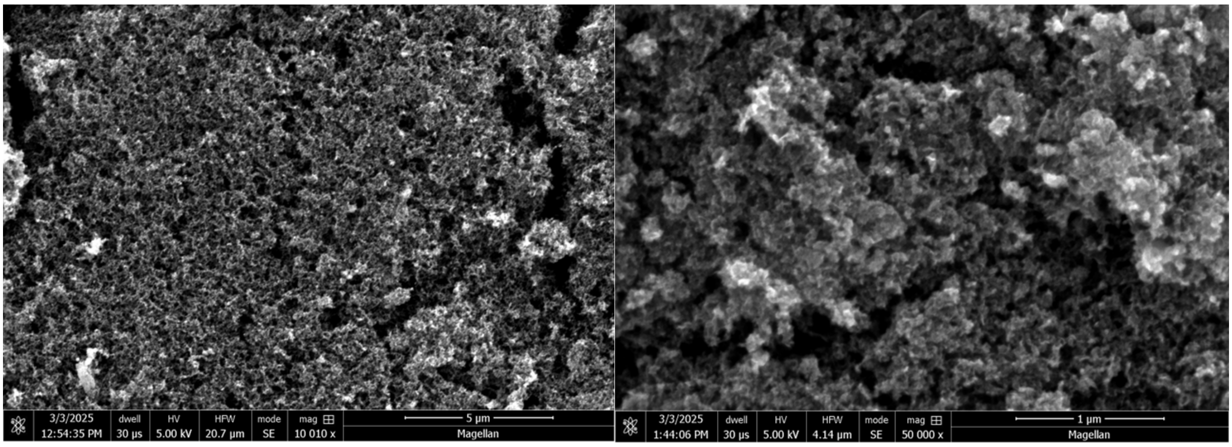


Figure 12 - Scanning Electron Microscopy Images of Graphene Produced at UU

Carbon Analysis Summary

The following data table summarises the measurements obtained from several different samples.

Table 7 - Graphene sample results

Sample	Bulk Density (g/L)	BET	TGA	Raman	Raman	Raman
-	-	Specific Surface Area (m^2/g)	Decomposition Peak (C)	I(D)/I(G)	I(2D)/I(G)	FWHM(G)
250128-UU100-B	16.2	331.4	684.4	1.4	0.84	48.71
250128-UU100-B	13.4	297.1	677.6	1.45	0.84	49.63
250303-UU100	23.1	310.6	604.1	1.44	0.94	47.86

The produced carbon has a graphitic (sp2) carbon structure that has turbostratic (random) alignment between layers leading to electronic decoupling. There is a highly disordered sp2 structure and impurity from the gas or other source may be present, reducing thermal stability. Approximately 70% of the material consists of graphitic solid carbon with the remainder being made up of complex hydrocarbon mixture adsorbed/bonded to the surface of the high surface area carbon. A SSA of ~300 m^2/g combined with sp2 crystalline structure confirms that the material is graphene-like. SEM and bulk density measurements confirm the material is highly 3D structured and interconnected while being made up of small 20-300nm spheroid/flake like particulates that make up the 3D foam/web. Removal of the adsorbed hydrocarbons shows the underlying graphene structure to have a significantly increased SSA of ~850 m^2/g, a very high value correlating to ~3 graphene layers on average.

In summary, the material produced at UU is graphitic with a very low average number of layers and high surface area compared to graphene produced from conventional biomethane supply.

4.2 Hydrogen Production

Qualitative Analysis

The full mass spectrometer scan for qualitative purposes shows a good match to the anticipated major exhaust species.

All graphs use the following key:

The scatter series (black line in Figure 14) shows the measured mass spectrum profile of the exhaust gas (two repeat scans overlaid). The bar series in Figure 14 represents the fitment of fragmentation patterns of the anticipated gases applied by the subsequent semi-quantitative analysis.

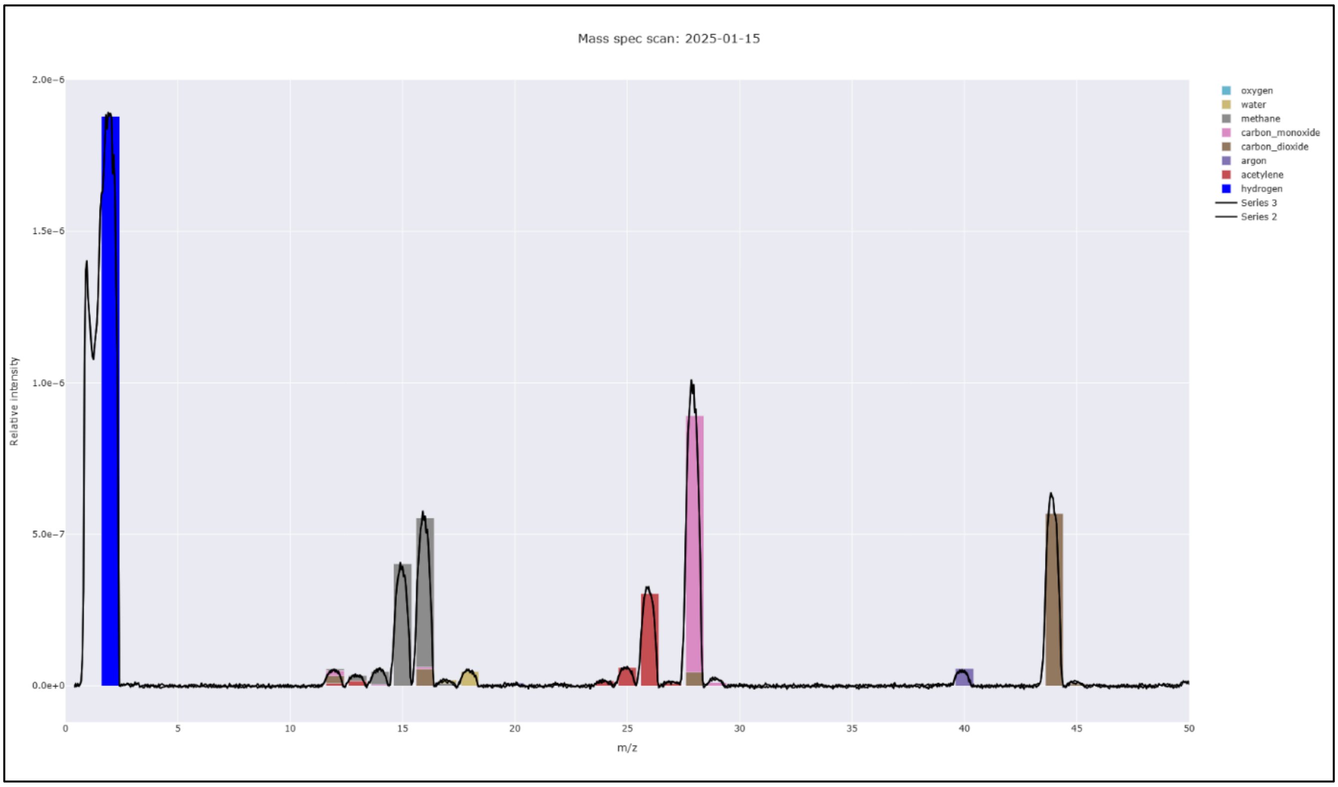


Figure 13 - Full mass spectrum of exhaust gases - 15th January 2025

Semi Quantitative Analysis

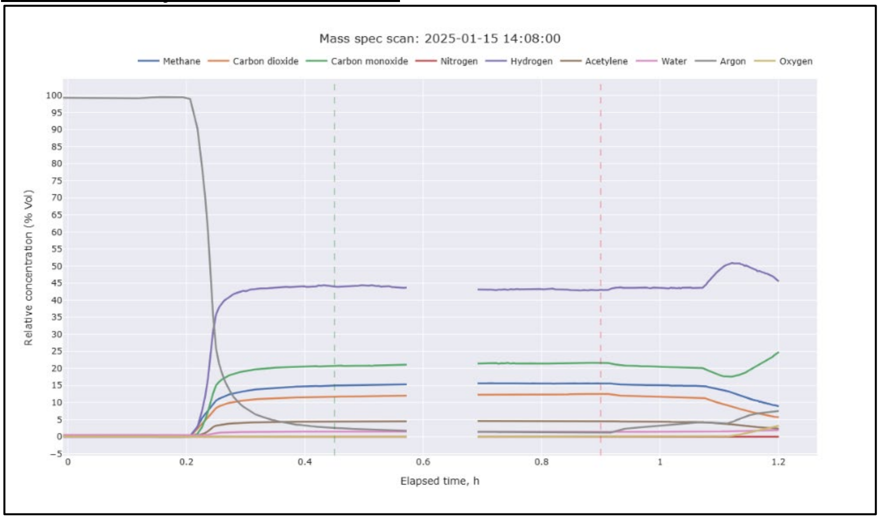
The mass spectrometer data presented here is semi-quantitative. While trends and relative changes remain meaningful, absolute concentrations may be subject to systematic errors.

- Quantification is performed relatively, based on the partial pressure of a given gas component compared to the sum of partial pressures of all gases included in the method.
- The qualitative analysis provides confidence that all the major gases in the exhaust have been accounted for by the method (as we do not see any unaccounted-for peaks).
- Nitrogen is omitted from the method, whose presence is not expected during steady state operation.

The graphs below show the composition of the LOOP exhaust gas stream (hydrogen syngas) over time, for each time the LOOP was run consistently.

Table 8 - Mass Spectrometer screen prints during operation

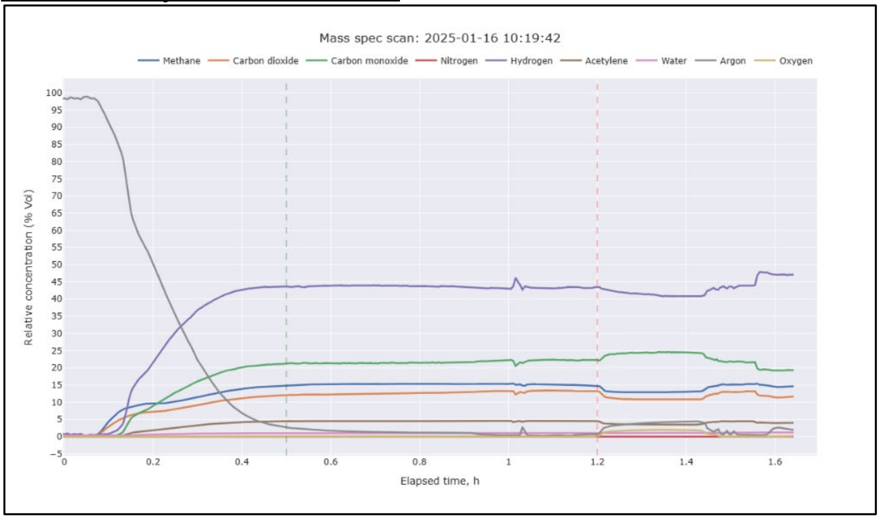
Measurement datetime: **Graph of concentration vs time:**	**Semi-quantitative volume fraction results** **(median value between bounds in graph, vertical dotted green and red line)**
15th January 2025 14:08:00:	



Between 0.57 and 0.69 hours, the full mass spec scan was conducted (as detailed in ‘Qualitative analysis’, Figure 13).

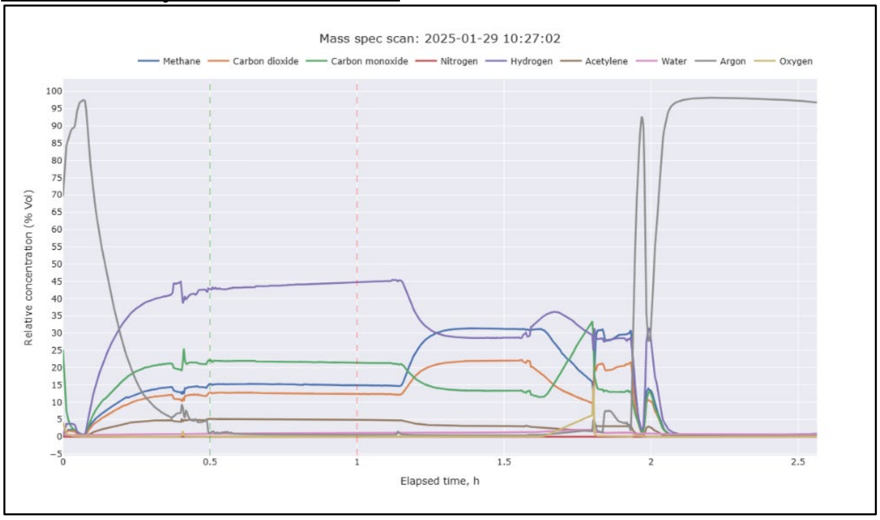
Time Range	0.45-0.9
Methane	15.59601
Carbon dioxide	12.33455
Carbon monoxide	21.43589
Nitrogen	0
Hydrogen	43.228
Acetylene	4.583014
Water	1.467293
Argon	1.363081
Oxygen	0
Elapsed time (h)	0.7325

16th January 2025 10:19:42:



Time Range	0.5-1.2
Methane	15.28841
Carbon dioxide	12.76891
Carbon monoxide	21.51986
Nitrogen	0
Hydrogen	43.68909
Acetylene	4.521057
Water	1.03864
Argon	1.124641
Oxygen	0
Elapsed time (h)	0.850833

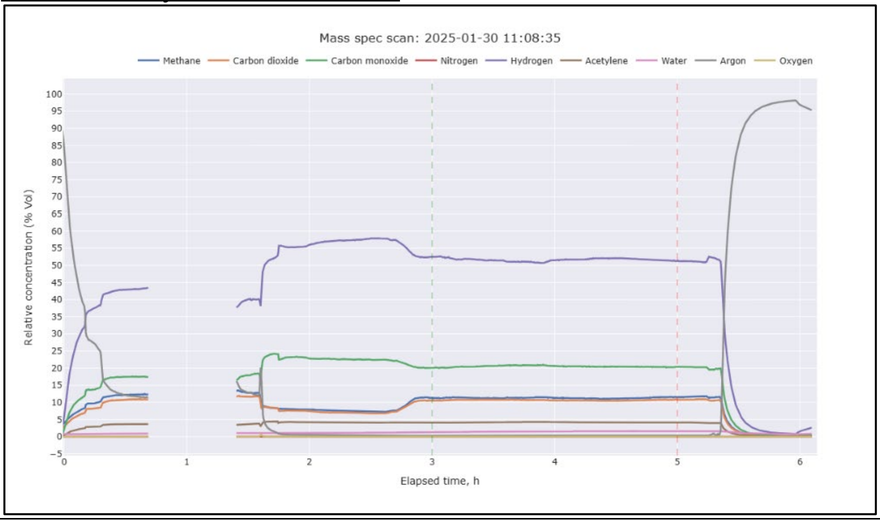
29th January 2025 10:27:02:



Time Range	0.5-1.0
Methane	15.17158
Carbon dioxide	12.62616
Carbon monoxide	21.72236
Nitrogen	0
Hydrogen	43.76448
Acetylene	5.011767
Water	1.010528
Argon	0.630795
Oxygen	0.000456
Elapsed time (h)	0.736389

At 1.15 hours, H_2, CO and C_2H_2 levels drop whilst CH_4 and CO_2 rise. It is believed this was due to plasma shutdown on one of the two nozzles but feedstock flow maintained through the 'unlit' nozzle, diluting the products of the other nozzle.

30th January 2025 11:08:35:



Time Range	3.0-5.0
Methane	11.28416
Carbon dioxide	10.68779
Carbon monoxide	20.43145
Nitrogen	0
Hydrogen	51.66993
Acetylene	4.129617
Water	1.530762
Argon	0.267555
Oxygen	0
Elapsed time (h)	4.006667

The graphs above show the gas, including hydrogen, produced by LOOP at various points in the trial. Graphs from the 15 and 16 January show the LOOP system starting, the system transitions from the argon purge gas to a stable mixture comprising hydrogen, methane, CO2 and CO plus a number of smaller constituents. Comparison of the various dates shows a consistent hydrogen production of between 41% and 51% of the LOOP process exhaust. Data from the 29 January shows the impact of reducing LOOP chamber production to a single nozzle, illustrating impact of LOOP operating parameters on the output gas composition and hydrogen recovery.

5.0 Carbon

5.1 Overview

The purpose of the LOOP LCA is to demonstrate the feasibility of plasma-based technology to produce hydrogen and graphene from biogas as a decarbonisation device as well as assessing impacts in other environmental categories. This report details the LCA conducted to achieve the following objectives:

- **Environmental Impact:** Map the environmental impact of the technology and assess its alignment with the UK Government Low Carbon Hydrogen Standard.
- **Greenhouse gas (GHG) emissions:** Understand the influence of implementing the Levidian LOOP technology on greenhouse gas emissions.
- **Sensitivity analysis:** Highlight areas of sensitivity in assumptions at the current stage of maturity of the technology.
- **Recommendations:** Provide recommendations for further study as the technology continues to evolve.

5.2 Scope

The study evaluated:

- The carbon footprint of hydrogen and graphene production at the point of production.
- Environmental burdens and benefits of the LOOP technology.
- Different scenarios of biogas use:
- Co-generation and on-site use.
- Upgrading to biomethane and injection into the grid.
- Use for hydrogen/graphene production in the LOOP unit.

In addition to greenhouse gas emissions, the study assessed impacts on: toxicity, ecotoxicity, water consumption, eutrophication, ionizing radiation, fossil resource scarcity, global warming, ozone formation, acidification, fine particulate matter formation, stratospheric ozone depletion, and mineral resource scarcity.

5.3 Methodology

This LCA study is aligned to the guidelines of the Low Carbon Hydrogen Standard, ISO 14040/44. The ReCiPe methodology was used for quantification of environmental impact, including global warming (quantified as greenhouse gases emissions). The model was developed in SimaPro (version 9.6.0.1). In addition to data obtained directly from Partners (Levidian and UU), Ecoinvent (version 3.10) inventories were used.

The data and findings presented are based on the most recent and accurate information available at the time of the study. However, it is important to note that the pilot plant was not fully operational during the data collection phase, leading to certain limitations in the data obtained.

To address these limitations, the study incorporated data from practical operations on various feedstocks, subsequent laboratory-scale tests, practical observations from the pilot plant, and theoretical data based on established chemical and physical processes (source: Levidian). These measures were implemented to enhance the robustness and reliability of the LCA study.

While the findings provide valuable insights into the environmental performance of the LOOP technology, they should be considered within the context of the data limitations and assumptions. Further research and validation are recommended to fully realize the potential benefits and address any remaining uncertainties.

Table 9 - LCA Assumptions

	Assumption	Value	Unit	Comment	Reference
1	Hydrogen output from LOOP 1000	9.6	kg/hr	Hydrogen production rate calculated based on theoretical proportions and data from Scienco (laboratory analysis) and Levidian.	Levidian and Jacobs
2	Graphene output – LOOP 1000	10.6	g/m^3	LOOP 1000, the output is linearly extrapolated. On methane feed, LOOP 100 graphene output is 66.67 g/m^3 feed;	Levidian and Jacobs
3	Operational availability	85%		Based on Levidian's predictions.	Levidian
4	Methane input	150	m^3/h		Levidian
5	Methane content in biogas	60.8%		Average from samples collected during the pilot plant operations.	Composition of input and output gas.
6	Biogas input to LOOP	150	m^3/h	Estimation of the flow rate of biogas input to LOOP1000	Levidian and Jacobs
7	Electricity usage	700	kWh/h	The power consumption is 7 kWh for each 1.5 m^3 of biogas.	Levidian and Jacobs
8	H_2 conversion 1 MJ to kWh	3.6		To convert from a per MJ H_2 measure to a per kWh H2 measure, multiply the per MJ H_2 measure by 3.6	Data Annex, LCH Standard
9	H_2 conversion 2 MJ to kWh	120.0	MJ/m^3	To convert from a per MJLHV pure H_2 measure to a per kg pure H_2 measure, multiply the per MJLHV pure H_2 measure by 120.0 MJLHV/kg H_2	Data Annex, LCH Standard
10	Daily biogas production	127,716.04	Nm^3/d	Based on MBC biogas production data delivered by UU (08/08/23 - 07/08/24)	UU – Biogas production Data
11	Voltage (Maximum)	>600	V	Absolute Maximum Voltage for LOOP 100 equipment is 600 V.	ANSI C84.1
12	Hydrogen output purity (post VPSA)	80%			Levidian
13	Hydrogen LHV	120	MJ/kg		LCHS
14	Diesel energy content	4.66	l/kg H_2	To quantify how much diesel fuel can be avoided by using 1 kg of hydrogen fuel in a heavy goods vehicle (HGV) delivery truck, the energy content and efficiency of both fuels were compared.	Toyne, D. L., Schmuecker, J., & Ayres, W. (2015).
15	Avoided Cement due to graphene use in concrete	200	Kg/kgC	To estimate how much clinker/cement may be avoided by using 1 kg of graphene	The Graphene Council.

5.4 Key Findings

The Levidian LOOP technology exhibits a greenhouse gas emissions impact, with total emissions of 140.39 $gCO_2eq/MJLHV$. This exceeds the threshold set by the UK Low Carbon Hydrogen Standard. Refer to Table 10 for detailed emissions data.

Table 10 - Summary of carbon LCA results - Hydrogen

	Total Emissions gCO2eq/MJLHV
Feedstock (Upstream) Emissions	43.29
Input Materials	30.2
Production Emissions	0.04
Energy Supply	70.57
CO2 Capture	0
CO_2 Sequestration	0
Solid Carbon Distribution	0.03
Solid Carbon Sequestration	-5.21
Compression and Purification	2.37
Fossil Waste/Residue Counterfactual	0
Total	140.39

A key element of discussion within the project team during the development of the LCA has been the inclusion of feedstock emissions. These are arguably evident regardless of the downstream process and would therefore be incurred if using the current combined heat and power system or the LOOP process. They could therefore be removed from this assessment, however, we have chosen to include them so that a holistic view can be achieved. The energy supply emissions may also vary significantly depending on the source of the feed power to the LOOP. At the trial site the electrical supply is completely generated on site from the combined heat and power engines, however, this may not be the case at other locations. We have again included the figures so that potential future users of the technology have a thorough understanding before adoption.

Table 11 summarises the LCA results for hydrogen production in the LOOP system, using biogas as feedstock. The table highlights impact categories deemed significant to the environment.

Table 11 - Summary of LCA results (other impact categories) - Hydrogen

Impact Category	Normalized Impact	Characterized Impact	Unit
Global Warming	0.00236	18.864	kg CO_2 eq
Ionizing Radiation	0.00295	1.4169	kBq Co-60 eq
Terrestrial Ecotoxicity	0.00286	43.509	kg 1,4-DCB
Human Carcinogenic Toxicity	0.00479	0.049	kg 1,4-DCB
Fossil Resource Scarcity	0.00319	3.129	kg oil eq

Key areas of sensitivity at the current stage of maturity of the technology include feedstock variability, energy supply efficiency, and carbon dioxide capture and sequestration effectiveness. These areas are critical for understanding the potential variability in the environmental impact.

The study offers several suggestions for further research and potential improvements to enhance the environmental performance of the LOOP technology. These recommendations include:

- **Further exploration of GHG reduction potential:** Continue investigating the capabilities of LOOP to achieve greater reductions in GHG emissions. This includes refining processes, improving efficiency, and exploring innovative approaches to minimise carbon footprints.
- **Optimisation of environmental performance:** Identify and implement specific improvements to optimise the environmental performance of the LOOP technology. This may involve enhancing feedstock utilisation, improving energy efficiency, and integrating advanced purification and sequestration techniques.
- **Validation and expansion of applications:** Conduct additional studies to validate the findings of this LCA and explore new applications of the LOOP technology. This includes pilot projects, real-world trials, and collaboration with industry partners to assess the technology's feasibility and benefits in various contexts.

Additional comparative analysis was conducted for various scenarios of biogas use in the LOOP system and combined heat and power units. Table 12 presents a comparison of the scenarios analysed within the scope of this project. Table 13 compares the LCA results for different biogas utilisation scenarios.

Table 12 - Comparison of analysed scenarios

Aspect	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Biogas Allocation to LOOP	0%	25%	50%	75%
Biogas Allocation to CHP (Electricity and Heat Production)	100%	75%	50%	25%
Energy and Fuels Import	No fossil natural gas is imported. All electricity and heat demands are fulfilled by the CHP system utilising site-produced biogas.	No fossil natural gas is imported. Variant A/Variant B	No fossil natural gas is imported. Variant A/Variant B	No fossil natural gas is imported. Variant A/Variant B

Variant A: *The deficit in electricity is compensated by utilising hydrogen in CHPs. No direct GHG Emissions associated with use of hydrogen in this system.*
Variant B: *The deficit in electricity generated in CHP is compensated by utilising grid electricity.*
Grid Decarbonisation Factor: *All scenarios were calculated including grid decarbonisation factor. Used Ecoinvent average grid emissions (in Great Britain) as benchmark, 50% GHG emissions reduction and 95% emission reduction.*

Table 13 - Summary of comparative LCA results - Business as Usual/LOOP1000 (kgCO2e/m3 biogas processed)

	Scenario 0 (0% biogas to LOOP)	Scenario 1A (25% biogas to LOOP)	Scenario 1B (25% biogas to LOOP)	Scenario 2A (50% biogas to LOOP)	Scenario 2B (50% biogas to LOOP)	Scenario 3A (75% biogas to LOOP)	Scenario 3B (75% biogas to LOOP)
2023 grid	0.292	0.596	0.771	0.712	1.063	1.016	1.540
50% lower grid Carbon	0.292	0.430	0.517	0.463	0.638	0.601	0.863
Decarbonised grid	0.292	0.283	0.291	0.243	0.260	0.234	0.260

Future Carbon Intensity

Future deployments of LOOP can benefit from three key improvements to the carbon intensity:

1. **Use of renewable energy in the electricity supply.** UK grid electricity contributed 70.57 gCO_2eq/MJ LHV H_2 to GHG emissions. However, if future projects incorporate renewable energy sources or hydrogen-to-power CHP, emissions could fall significantly, with decarbonised scenarios reducing emissions to below the LCHS threshold.
2. **Input Materials – Argon Usage:** Switching inert gas to nitrogen would reduce emissions associated with argon supply. Nitrogen emits less than 25% of the emissions of argon.
3. **Allocating feedstock emissions by energy:** The figures above allocate varying percentages of upstream emissions from biogas production to LOOP. A typical LOOP deployment would utilise the remaining gases for energy or heat production, so the feedstock emission can be allocated based on the proportion of output energy associated with the two gas streams. This would allocate 21% of biogas emissions to LOOP.

Implementing these measures would result in an emissions factor of 12.97 gCO_2e/MJ LJV H_2, comfortably below the threshold set out by LCHS. The impact of the various factors in shown in Figure 14 below.

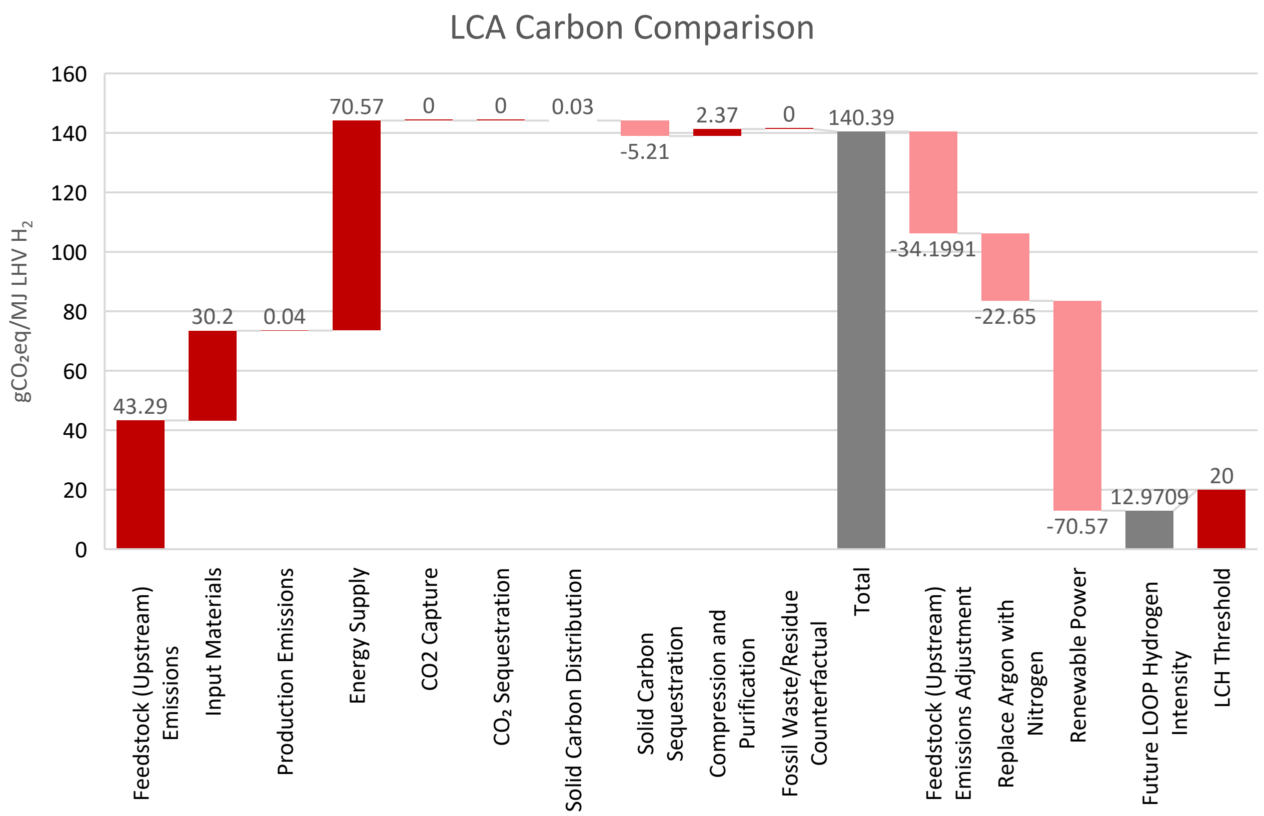


Figure 14 - Factors Influencing Carbon Intensity of Hydrogen from LOOP

6.0 Social Value

Jacobs were commissioned by UU to produce two deliverables to support understanding, delivery, and management of social value throughout LOOP Programme Phase 2. These were:

- **LOOP Phase 2 Social Value Strategy**: Defining the vision and priorities for social value during LOOP Programme Phase 2, with associated framework of commitments, actions, and performance targets.
- **Social Value Outcome Performance Report**: Performance report on the social value achieved through the delivery of LOOP Programme Phase 2, in line with the commitments made as part of the social value strategy.

The social value strategy establishes a social value framework for LOOP Phase 2, which is proportionate to the project scale. Informed by desk-based literature assessment, community needs assessment, and workshop with LOOP Phase 2 delivery partners, the strategy focuses on working with stakeholders to produce meaningful outcomes in alignment with the following priorities from the UK Social Value Model:

- **Reducing economic inequality** by supporting training and education, engaging with educational institutions, encouraging students and other members of the community to pursue professional education and careers in science, technology, engineering and maths (STEM), the provision of internships, and employability mentors. (Model Award Criteria (MAC) 2.2)
- **Increasing regional suppliers' resilience and** capacity through support of local small and medium sized enterprises (SMEs) and the upskilling around new and growth technology areas linked to the LOOP programme. (MAC 3.1, 3.2)
- **Supporting effective stewardship of the local environment** through increasing knowledge and engagement with environmental principles across LOOP programme stakeholders. (MAC 4.2).
- **Promoting equal opportunity** through increasing accessibility and engagement with target communities in the current delivery of LOOP and future roll-out phases. (MAC 6.1, 6.3).
- **Improving wellbeing** through investing in supporting the workforce deployed in delivering LOOP Phase 2 and embedding opportunities for engaging with community stakeholders (MAC 7.1, 8.1).

This strategy is underpinned by an implementation plan that sets out a series of commitments across governance, measurement, reporting, stakeholder engagement, and feedback and improvement, to best ensure commitments around social value generation are delivered. In doing so, this helps to ensure the long-term potential benefits of LOOP technologies are best supported, helping inform future delivery phases.

In delivery, the Delivery Partners were able to meet most of their commitments around value creation over the course of LOOP Programme Phase 2, with several of the agreed targets exceeded. These include the involvement of two interns during the delivery of the project at Levidian in Cambridge. The interns were involved in the design and build of the LOOP process and has provided them with direct experience of supporting the development of new technology and the skills required. Several publications have also been issued during the course of the project that highlight the LOOP technology and its products. These have mainly been online through partner organisation social media accounts and through the services of Spring as a knowledge sharing enterprise. In addition to this the project team have been increasingly engaging through online and in-person presentations including at the European Biosolids and Bioresources Conference 2024 in Manchester attended by over 1000 professionals from across the wastewater industry.

Their outputs have helped to create positive outcomes in reducing economic inequality through employment and skills, supported increasing supplier resiliency and market readiness through engagement activities, and promoted equal opportunity and workforce wellbeing through embedding of responsible business practices.

The Social Value Report and findings will be used by the LOOP Delivery Partners and wider stakeholders to reflect on processes and achievements around social value creation through this phase of work, helping to inform decision-making around future delivery phases of the LOOP Programme and associated innovation projects. A summary of the Delivery Partners commitments and achievements can be seen in the following table and is discussed in further detail in the Social Value report completed as part of this project.

Table 14 - Summary of social value achievements

PPN 06/20 MAC	Social Value (SV) Priority Outcome(s)	Performance Target	Performance Achieved
2.2	Reduce economic inequality by supporting training and education, engaging with educational institutions, promoting STEM careers, and providing internships and employability mentors	Track no. of new jobs created.	0
2.2	-	Track % of Full Time Equivalent (FTE) local to Greater Manchester Area.	96%
2.2	-	1 week training (work experience) in low carbon technologies	1 week
2.2	-	1 Internship position offered for training in low carbon technologies	2 Interns deployed
3.1, 3.2	Increasing regional suppliers' resilience and capacity through support of local SMEs and the upskilling in new and growth technology areas linked to the LOOP programme.	Track %/£ of total spend through contract with SMEs, including specified materials and services.	51%
3.1, 3.2	-	2 non-academic publications published	6
4.2	Supporting effective stewardship of the local environment through increasing knowledge and engagement with environmental principles across LOOP programme stakeholders.	10 young people engaged in careers and skills development activities	0
6.1, 6.3	Promoting equal opportunity through increasing accessibility and engagement with target communities in the current delivery of LOOP and future roll-out phases.	100% of workforce paid real living wage	100%
6.1, 6.3	-	100% of deployed staff trained in EDI	100%
6.1, 6.3	-	100% of supply chain compliant with Modern Slavery Act 2015	100%
7.1, 8.1	Improving wellbeing through investing in LOOP Phase 2 workforce and embedding opportunities for engaging with community stakeholders	100% of deployed staff completed health & safety training	100%
7.1, 8.1	-	50 hours per year volunteering with groups / charities	0

7.0 Commercialisation

Our approach to understanding commercialisation of the LOOP process and its associated products (graphene and hydrogen) has been to engage experts from different consultancies and academia.

- Levidian have provided their expert view of both the LOOP process and the potential market opportunities for graphene.

- UU have provided details of further opportunities in the North-West of England regarding the installation of further LOOP processes as a means of maximising the benefits of biogas.
- Liverpool John Moores University have supported the project team through their detailed understanding of the hydrogen opportunity across the Liverpool City Region. This has been combined with discussions with members of the Liverpool City Region Combined Authority (LCRCA) to understand their proposals for the take-up of hydrogen as a fuel.

7.1 LOOP

Levidian's LOOP technology offers a compelling solution for any biogas producing industry wanting to advance towards net zero goals. The patented LOOP process was originally developed by Levidian to produce graphene from natural gas at scale, with hydrogen gas being a waste by-product. However, with increased global focus on reducing GHG emissions and a transition away from fossil fuels, the team recognised that the LOOP could be successfully utilised as a method of producing low-carbon hydrogen, helping to accelerate the UK's legislative requirement and international obligations to achieve net zero emissions by 2050.

In the wastewater context, the main competitor to LOOP is use of biogas in CHP or via methanation for injection into the gas grid. LOOP provides an alternative means of processing biogas to produce hydrogen, graphene and combustible gas as opposed to electricity and heat provided by the CHP. The relative commercial advantage of LOOP is based on the prevailing value of electricity and heat, relative to the value of hydrogen and graphene.

7.2 Hydrogen

Hydrogen is expected to play one of the leading roles in the decarbonisation of the UK energy system, contributing to the net-zero target by 2050. The UK Government is committed to delivering a world-class hydrogen sector as part of its Clean Energy Superpower and Growth Missions, for example through the strategic investment of £500 million to develop the first regional hydrogen transport and storage network as part of its wider commitment to scaling up low-carbon hydrogen infrastructure.

As a versatile energy source, hydrogen can be used in various sectors, including transportation, industry, and power generation, emphasising its competitive advantages such as:

- Hydrogen, unlike other gases, does not emit any CO_2 at the point of use, which makes it a cleaner alternative to traditional fossil fuels, significantly reducing greenhouse gas emissions.
- Hydrogen offers an opportunity for greater fuel efficiency – traditional combustion plants typically have efficiencies of around 35%, whereas hydrogen fuel cells can achieve efficiencies of at least 60%. This higher efficiency means that less fuel is needed to produce the same amount of energy, further reducing overall carbon emissions.

Hydrogen can be stored and transported, helping to balance supply and demand on the power grid, which is not always suitable with other energy sources.

7.3 Graphene

Graphene is a single layer of carbon atoms arranged in a honeycomb-like pattern with exceptional strength, conductivity, and versatility, that is transforming industries by enabling advancements in electronics, energy storage, and composite materials.

Beyond single-layer graphene, there is a wider graphene family of materials, which includes variants such as few-layer graphenes and nanoplatelets, graphene oxide, and reduced graphene oxide. These materials differ in structure, composition, and performance, making them suited to different applications.

Generated as a valuable byproduct of the LOOP process, graphene possesses the unique properties as detailed below:

- **Strength**: Graphene's application as an additive in carbon-intensive materials, such as concrete, enhances their strength. This allows building contractors to use less of those materials to achieve the same structural stability, thereby reducing the overall carbon footprint of construction projects. The increased durability of graphene-enhanced concrete extends the lifespan of structures, leading to fewer repairs and replacements, which further contributes to decarbonisation efforts. The aerospace and motorsport industries are increasingly adopting graphene for composite materials due to its exceptional strength.
- **Electrical Conductivity and Electron Mobility**: Graphene's ability to conduct electricity 100 times faster than silicon is revolutionising the electronics industry, leading to improvements in high-speed transistors, spin devices, and semiconductor memory.
- **Surface-to-Weight Ratio**: Graphene's large surface is ideal for energy generation and storage applications, including fuel cells, batteries, and supercapacitors.
- **Barrier Material**: Graphene's impermeability, when defect-free, is exemplary for durable and protective coatings, paints, and adhesives.
- **Light Transparency**: With 97.7% transparency, graphene is becoming pivotal in optical electronics, such as touchscreens and LCDs, as well as in telecommunications for fibre optic networks and wireless antennas.
- **Carbon Capture**: Being resistant to conversion back into CO_2, it serves as an effective carbon sink, which is crucial for long-term carbon sequestration. Its permanence ensures that the captured carbon remains stored and does not get released into the atmosphere.

Based on the research done in the Graphene Roadmap brief to compare various market reports, it was established that the global graphene market has shown continuous growth over the past decade to reach an average estimated global annual revenue of 380 million US$ in 2022 which is nearly 300 million GBP (forecast range between 50 million and 1.1 billion US$ or 40 to 900 million GBP), as demonstrated in the following graph.

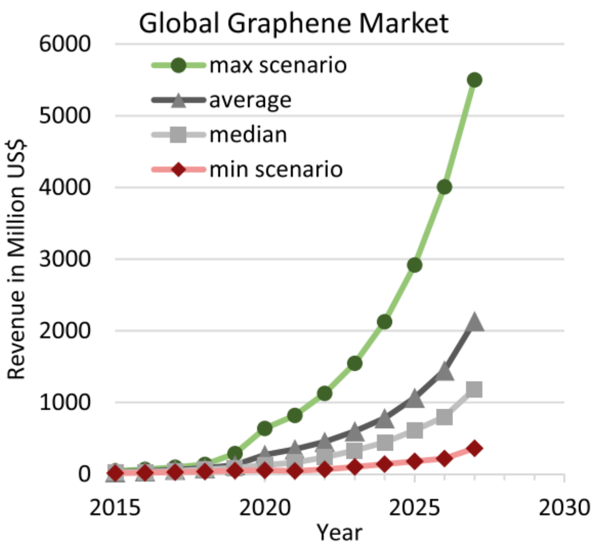


Figure 15 - Predicted global graphene revenue

While the current size of the graphene market is much smaller in comparison to the markets for graphite or carbon black, since its discovery in 2004, it has experienced rapid growth. With significant market expansion predicted, reaching an estimated $1.5 billion by 2027, demand for graphene is expected to continue increasing, potentially reaching a market value of up to $5.5 billion in the next decade. This demonstrates its potential to disrupt numerous industries with its extraordinary properties and diverse applications.

7.4 Commercialisation Potential

Our commercialisation planning has reviewed potential at local, regional, national and international scales.

Local Level

At a local level, we have reviewed potential impacts of LOOP application at individual UU sites. These sites could be strategically targeted to maximise LOOP's initial impact as the technology is being rolled out. The sites would provide a stable environment with a continuous biogas supply, where performance could be managed and monitored in line with the systems already in place at UU.

Across different sites, UU employ different types of digesters, which affect the output volumes of the biogas. Most of the smaller sites have conventional anaerobic digesters. Other (fewer) sites use more advance types such as Enhanced Enzymic Hydrolysis (EEH) and Thermal Hydrolysis Process (THP). The latter achieves enhanced treated sludge which subsequently leads to larger amounts of biogas produced. With the system being modular, LOOP can be adapted to the characteristics of each site, considering its size, capacity for biogas production as well as possible means of realisation on site (e.g. established gas-to-grid connection).

In Phase 1, theoretical maximum hydrogen and graphene production from sludge biogas has been assessed at various UU sites using the following assumptions in table 15.

Table 15 - Production calculation conversions and assumptions

Methane content	65% of biogas
Methane, m3 to kg conversion factor	0.671
Graphene output per 100kg of methane	27 kg
Hydrogen output per 100kg of methane	21 kg

The maximum potential volumes have been calculated based on methane volumes from biogas produced (table below), using the UU total raw sludge treated per year as per Annual Performance Tables (APR) for 2024.

While data specific to LOOP's performance with biogas is currently limited, this Commercialisation Plan utilises a robust proxy to showcase its potential. By modelling the system's operation using methane, mirroring the established use of natural gas in LOOP demonstrations, we can effectively illustrate the technology's scalability and impact. This approach provides valuable insights into the potential outcomes of utilising biogas as a feedstock for LOOP, paving the way for further investigation and optimisation.

Table 16 - UU site potential production

United Utilities Site	No. of digesters	Type of digester	Biogas (m^3/y)	Methane (t/y)	Hydrogen Production (t/y)	Graphene Production (t/y)
Blackburn	4	EEH	6.2M	2,718	571	734
Bolton	3	Conventional	4.2M	1,811	380	489
Burnley	1	THP	2.2M	964	202	260
Bury	3	Conventional	2.1M	907	190	245
Ellesmere Port	3	ATAD	3.2M	1,394	293	376
Lancaster	3	EEH	3.2M	1,382	290	373
Leigh	1	THP	2.8M	1,227	258	331
Liverpool	4	Conventional	3.7M	1,632	343	441
MBC	8	THP	45.6M	19,870	4,173	5,365
Oldham	4	Conventional	2.0M	858	180	232
Southport	2	Conventional	1.0M	442	93	119
St Helens	2	Conventional	0.7M	326	68	88
Stockport	3	Conventional	1.3M	561	118	152
Warrington North	3	Conventional	2.7M	1,157	243	312
Total Estimated Output				**35,249**	**7,402**	**9,517**

Localised hydrogen production could offer the following benefits to UU:

- **Reducing emissions**: Having LOOP at those sites would support UU's decarbonisation efforts in reaching their sustainability targets, significantly reducing CO_2 emissions as well as methane emissions.
- **Enforcing sustainable sources of energy**: As LOOP-produced hydrogen can be looped back to the UU sites as a source of energy, this will unlock an opportunity for UU to become energy self-sufficient via employing green hydrogen and relying less on the external sources.
- **Transport**: There are opportunities for the hydrogen to be utilised to power hydrogen-fuelled vehicles, aligning with UUs' ambitious objective of transitioning all 1,600 vehicles to run on electricity or alternative fuels by 2028.
- **Energy storage**: Hydrogen fuel cells offer a dependable backup power solution for critical infrastructure, offering continuous operation during power outages.

In the short-term, the most feasible scenario to realise hydrogen at a local level is feeding it to the Combined Heat and Power (CHP) units at UU sites, provided the infrastructure is adapted accordingly to take hydrogen as input. Currently, when the sludge is treated into biogas, a proportion of this biogas is used in CHP systems directly to generate heat/electricity on-site whilst the remaining biogas can then be upgraded to biomethane and be injected to the energy grid. With LOOP, some of this biogas can be directed to produce hydrogen which would be more energy-efficient than direct biogas.

Regional Level

The primary differentiator between the local and regional markets lies in the scale and scope. While the local market focuses on specific UU sites, the regional market encompasses a broader range of industrial and utility sites, providing a larger scale for deployment and a greater potential for impact.

The regional market presents numerous opportunities for Levidian, where LOOP can seek opportunities not only within the wastewater sector but go beyond and see where it can be integrated into more complicated systems. The benefits from realising hydrogen and graphene at the regional level will mirror the opportunities unlocked at a local level. However, wider production could enhance these advantages by offering the following benefits:

- **Export Potential:** Expanding regionally not only enhances LOOP's local market opportunities but also amplifies its impact on the green economy. For instance, UUs proximity to the HyNet gas distribution network presents an opportunity to export hydrogen. By aligning with these initiatives, LOOP can play a pivotal role in building a robust hydrogen economy, meeting both industrial and residential energy demands, and creating jobs in the green technology sector.
- **Research and Development:** High-quality graphene can be marketed to local manufacturers and research institutions, driving innovation within the community. Additionally, hydrogen produced on-site can be supplied to local companies for their operations, initiating partnerships and boosting the local green economy.
- **Transport:** Beyond powering company fleets, hydrogen can be used by Merseyside's transport sector to transition heavy goods vehicles and public transport to sustainable fuel sources.

Assessing infrastructure readiness at the regional level involves identifying and leveraging diverse biogas and methane sources across various industries. This comprehensive approach not only facilitates significant regional decarbonisation but also highlights LOOP's scalability and effectiveness. By demonstrating these benefits on a larger scale, LOOP can serve as a robust model for national and global applications, reinforcing its potential to drive widespread environmental and economic progress.

Some water sites use Anaerobic Digesters (ADs) to handle organic waste and produce biogas, which with LOOP can be converted into valuable hydrogen and graphene. If LOOP is integrated at water sites before the water reaches wastewater facilities, it can reduce greenhouse gas emissions and produce more clean hydrogen. Although water sites have more limited infrastructure compared to large-scale operations at wastewater treatment sites, they can still support ADs and biogas production, which may be sufficient for on-site energy needs and local applications, potentially making the smaller scale LOOP units (e.g. LOOP10) more applicable. Integrating LOOP at both water and wastewater sites will create a resilient infrastructure, ensuring a steady supply of hydrogen and graphene even if disruptions occur at one site. Additionally, water sites' visibility and accessibility to the public can enhance community awareness and support for sustainable practices, fostering innovation and environmental stewardship.

Liverpool City Region

Liverpool City Region (LCR) can be used as an example of a region where there are attractive opportunities for LOOP to be integrated in the decarbonisation system while simultaneously advancing regional goals.

LCR has significant advantages in several aspects of hydrogen developments, particularly in infrastructure readiness and industrial cluster synergy. The LCR has transformed from ranking among the top five UK industrial clusters for emissions to being a critical area in addressing the UK's climate challenges. Instrumental to this transformation was the commitment to the HyNet Project, which focuses on producing low carbon hydrogen, developing a network for capturing and storing CO_2 in geological formations under Liverpool Bay and a hydrogen distribution network serving sectors across the Northwest of England and North Wales. The following illustration presents the potential infrastructure that can be utilised in the LCR, which is where LOOP-produced hydrogen would allow to add value.

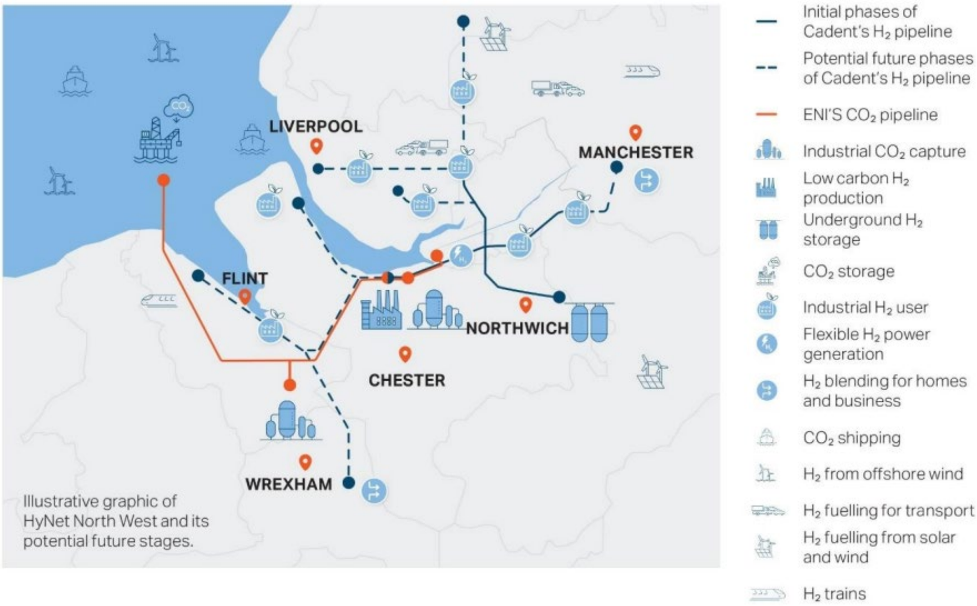


Figure 16 - HyNet route and facilities

Demand for hydrogen in LCR has been increasing as opportunities appear across various industries.

- **Industrial Consumption**:
  - **Hydrogen-fuelled commercial vehicles:** ULEMCo based in Sefton is a global pioneer of technology to convert commercial vehicles to be fuelled by hydrogen. They have recently been awarded £7.9 million of Government funding to develop hydrogen fuel technologies for emergency vehicles.
  - **Hydrogen in glass manufacturing:** Pilkington Glass, based in St Helens, Merseyside, has committed to an overall 30% reduction in carbon emissions by 2030, seeking to replace traditional fossil fuels.
- **Domestic Consumption**:
  - **Household heating:** Cadent, a gas distribution company, is responsible for half of the natural gas distribution networks in the UK. This company is embarking on a project that involves blending hydrogen with natural gas to supply households in Liverpool and Manchester.
- **Transport**
  - **Hydrogen-powered buses / aircrafts / trains:** There are emerging opportunities to supply public transport with hydrogen fuel, if low-carbon (e.g. green hydrogen) hydrogen is used to make these solutions compliant with net zero future. For instance:
    - In 2020, Alstom Transport (UK) Ltd announced plans to build a new 'Breeze' 600 series of Green Hydrogen trains. It is anticipated that the testing of these hydrogen-powered trains will be conducted in the Merseyside area.

- Budget airline EasyJet is accelerating its efforts to operating a hydrogen-fuelled aircraft, with an expectation to power 25 routes out of John Lennon Airport with hydrogen. Supporting the initiative, Rolls Royce has conducted a series of tests at its facilities solving the engineering challenges of chilling low-pressure hydrogen below -250°C, enabling its pumping into a jet engine.

- **Port Operation:** Hydrogen is a promising alternative to diesel for onshore port equipment that is challenging to electrify, such as heavy-duty shunting equipment and large industrial mobile cranes.

- **Heavy Goods Vehicles (HGVs):** All Internal Combustion Engine (ICE) powered HGVs will be banned by 2040, with some classes banned by 2035. Fuel cell electric vehicles (FCEVs) which use compressed hydrogen would then be ideal for heavy loads and point-to-point duty cycles with limited base charging.

Technical challenges in hydrogen production and storage, high supply chain costs, and the complexity of infrastructure modifications remain major obstacles to the widespread adoption of hydrogen. Moreover, hydrogen obtained from fossil fuels does not comply with the net zero objectives, hence its application is not entirely sustainable. However, with such a modular and adaptable technology as LOOP, production of clean low-carbon hydrogen may become more attainable, and the prices can be expected to become more competitive in comparison with other fuels.

National level

The national market for LOOP can be defined by the UK water industry and other biogas-producing sectors. Statistics show that currently a lot of energy is being produced from feedstock, specifically energy obtained from the anaerobic digestion, which in 2022 delivered 922,000 tonnes of oil equivalent, an increase of 3.2% compared to 2021.

Ten major water utilities in England and Wales have been assessed in the following table. Each have the capabilities to utilise the LOOP technology for hydrogen and graphene production. Some utility companies produce biomethane as well as biogas at sites, so approximate hydrogen and graphene production has been calculated for both gas inputs.

Table 17 - UK water industry potential production

Water Utility	Biogas (m^3/y)	Methane (t/y)	Hydrogen Production (t/y)	Graphene Production (t/y)
Thames Water	123,719,040	83,015	17,433	22,414
Severn Trent Water	101,868,525	68,354	14,354	18,456
United Utilities	72,133,130	48,401	10,164	13,068
Anglian Water	64,831,140	43,502	9,135	11,745
Yorkshire Water	45,660,945	30,638	6,434	8,272
Southern Water	38,310,000	25,706	5,398	6,941
Northumbrian Water	33,975,000	22,797	4,787	6,155
Dwr Cymru/Welsh Water	32,853,060	22,044	4,629	5,952
Wessex Water	19,880,100	13,340	2,801	3,602
South West Water	4,375,800	2,936	617	793
Total Estimated Output	**537,606,740**	**360,734**	**75,754**	**97,398**

Based on the above estimates, Thames Water, Severn Trent Water and United Utilities emerge as the greatest green hydrogen benefactors, each capable of producing over 10,000 tonnes annually with Levidian LOOP technology. While this scale would require significant renewable energy investment and may partially displace existing biogas utilisation, it unlocks a pathway to decarbonisation and energy independence. Furthermore, these water companies could collectively generate over 40,000 tonnes of valuable graphene per year, further diversifying revenue streams and contributing to a circular economy. This projection, based on maximum production potential and pilot study data, illustrates a compelling best-case scenario for these utilities to lead the charge in sustainable innovation.

The national market offers access to a diverse range of biogas sources beyond regional production, such as landfills, agricultural operations, and other industrial processes. As the market expands, LOOP's technology can be deployed across multiple industries while ensuring consistent performance and seamless integration. Economic viability becomes essential, as national deployment must ensure that the benefits of LOOP outweigh the costs associated with implementation, operation, and new regulation.

The needs at the national level differ significantly from those at the regional level in several key ways. National deployment involves operations on an expanded scale, integrating LOOP across multiple sites, requiring extensive infrastructure and coordination. At this scale, it will be crucial to standardise processes of deploying and operating LOOP, making sure that all wider regulations are met ubiquitously to ensure consistency and efficiency. Additionally, moving beyond the northwest region means applications for hydrogen and graphene can vary widely, from industrial use in manufacturing hubs to residential energy in urban areas. Therefore, national deployment will be driven by collaboration amongst a wide range of stakeholders, including government bodies, industry associations, and research institutions. This collaboration is crucial to navigate unique challenges and ensure the full potential of LOOP technology is realised.

Hydrogen production on a national level presents significant off-site opportunities, magnified with the government's strong support for a hydrogen economy.

- **Supply to Hydrogen Refuelling Stations:** The growing demand for FCEVs requires a reliable and widespread refuelling infrastructure. Currently, the UK has 15 public hydrogen fuel stations, but H2Green and Element 2 plan to expand this network to 800 stations by 2027 and 2,000 by 2030. Integrating LOOP on a national level can help meet this demand, supporting the development of a sustainable transport system and contributing to broader environmental and economic goals.
- **Export Potential:** The UK has the potential to become a major exporter of hydrogen, especially to continental Europe, where demand for green hydrogen is increasing.

Global Level

The global market for clean energy technologies like LOOP is growing rapidly as governments worldwide push for sustainable, low-carbon energy solutions. Like the UK, many countries have set ambitious goals to transition to alternative energy sources as part of their decarbonisation journey and so will be eager to accelerate their transition with cutting-edge technologies. The following table provides an overview of the global market opportunities that could be feasible.

Table 18 - Global potential markets

Region	Bioresource Availability	Energy Costs	Decarbonisation Targets	Hydrogen Strategy	LOOP Integration Feasibility
Middle East and North Africa (MENA)	The Middle East generates over 150 million tons of urban waste annually. Wastewater generation averages 80-200 litres per person per day, with sewage output rising by 25% annually. In Dubai, sewage generation increased from 50,000 m³/day in 1981 to 400,000 m³/day in 2006.	The MENA region has significant renewable energy advantages, including abundant sunlight, vast flat lands and strong coastal winds, leading to some of the world's lowest renewable power costs. Ten of the top 15 countries with the highest solar potential are in MENA. MENA countries could become key players in green hydrogen production and export, favoured by importers like Europe over "blue" (natural gas) and "pink" (nuclear) hydrogen.	Many MENA countries are committed to decarbonisation with ambitious targets. For instance, Saudi Arabia aims for net zero GHG emissions by 2060 and plans to cut carbon emissions by 278 million tonnes annually by 2030. These goals align with deploying LOOP technology to reduce GHG emissions annually.	Clean hydrogen from the MENA region has export potential to Japan, South Korea, and Europe, where it could command a premium. Early collaborations include Saudi Arabia's Green Hydrogen Company at NEOM, which plans to supply hydrogen to Europe via Air Products. Of the three global hydrogen export projects that have reached final investment decisions, two are in MENA. Oman's project aims to produce 38,000 tonnes of hydrogen annually, while Saudi Arabia's NEOM project targets 237,000 tonnes per year.	Saudi Arabia's heavy reliance on oil, which constitutes over 40% of its GDP, presents significant economic risks as global decarbonisation efforts intensify. Integrating LOOP technology can diversity Saudi Arabia's energy portfolio by converting local biogas into clean hydrogen. This shift can reduce oil dependence and enhance energy independence. The MENA region's abundant bioresources, such as urban waste and wastewater, offer substantial opportunities for biogas production. Leveraging these resources with LOOP technology can enhance existing bioresource management systems, building resilience against oil price fluctuations.
Europe	The EU has over 17,000 biogas plants, mostly decentralized CHP facilities. Around 400 produce biomethane, primarily in Germany, Sweden, and the UK, which is mainly injected into the natural gas grid or used in captive fleets. This presents an	Energy prices in Europe hit record highs in 2023, with electricity and natural gas rates still rising. Post-pandemic demand and the Ukraine crisis led to a global energy shortage, exacerbating EU energy inflation. Dependence on fossil fuel imports, low hydropower, and reduced nuclear capacity in	In 2023, the EU adopted proposals to cut net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels, aiming for climate neutrality by 2050. This goal, central to the European Green Deal, is legally binding under the European Climate Law.	The EU's Hydrogen Strategy aims for 10 million tonnes of renewable hydrogen by 2030 and carbon neutrality by 2050, with low-carbon hydrogen as a transitional source. It targets 40% domestic production of net-zero technologies by 2030 and 15% of global	Producing hydrogen locally from biogas with LOOP can enhance the EU's energy security, reducing reliance on fossil fuels. EU incentives for hydrogen production make LOOP technology a strategic asset, enhancing competitiveness and supporting

Region	Bioresource Availability	Energy Costs	Decarbonisation Targets	Hydrogen Strategy	LOOP Integration Feasibility
	opportunity for Levidian to integrate LOOP technology and direct a portion of the available biogas to create a more energy-efficient source of energy i.e. hydrogen.	France further increased prices. With volatile energy prices, efficient bioresource use and renewable energy production, like hydrogen, are increasingly crucial.		production by 2040, streamlining manufacturing procedures. Electrolysers and fuel cells are identified as net-zero technologies, eligible for support. REPowerEU plans to boost hydrogen consumption to 20 million tons annually by 2030.	decarbonisation at lower costs. LOOP converts organic waste into hydrogen and graphene, reducing landfill use and emissions. This supports the European Green Deal's Circular Economy Action Plan and the 2050 climate neutrality target by transforming waste into valuable resources. Given high energy costs in the region, energy-intensive hydrogen production methods like electrolysis may not be most feasible to apply, whereas LOOP can present a more competitive way to produce low-carbon hydrogen.
North America	The US biogas industry has potential for exponential growth, with over 15,000 new sites ready for development. These could produce 103 billion kWh of electricity annually, equivalent to removing 117 million cars from the road, and drive $45 billion in investment, creating 374,000 construction jobs and 25,000 permanent jobs.	North America's energy prices are generally lower due to significant production capabilities, with the US maintaining some of the lowest household electricity prices globally. Despite market fluctuations and fuel shortages in late 2021 and 2022, the US has stable, competitive energy costs, benefiting industries and consumers. This stability supports efficient bioresource use and renewable energy production, crucial for decarbonisation goals.	In recent years, the US and Canada have committed to climate action with emissions reduction targets and supportive policies for zero-emissions technologies. Both aim for net-zero emissions by 2050, with interim 2030 goals of a 40-45% reduction from 2005 levels in Canada and a 50-52% reduction in the US.	The Inflation Reduction Act (IRA) incentivises low-carbon fuels, including hydrogen, with tax credits under Sections 45V and 48. Canada funded two hydrogen projects through the Strategic Innovation Fund – Net Zero-Accelerator (SIF-NZA). Additionally, the Canada Infrastructure Bank (CIB) launched a $500 million initiative for charging and hydrogen refuelling infrastructure and provided $277	The US has about 2,300 biogas sites with $37.5 bn in investment. LOOP can capture methane emissions at these sites, converting them into hydrogen and graphene, reducing greenhouse gases and creating valuable by-products. The Southwire-Levidian collaboration demonstrates how LOOP technology can convert methane into hydrogen-rich gas within industrial processes, significantly reducing carbon

Region	Bioresource Availability	Energy Costs	Decarbonisation Targets	Hydrogen Strategy	LOOP Integration Feasibility
				million for the Varennes biorefinery and hydrogen electrolysis project. The CIB also funds front-end engineering and design (FEED) for hydrogen projects through its Project Acceleration program.	emissions. This is vital for North America's industrial sector, prioritising decarbonisation.

8.0 Lessons Learnt

The following table provides the lessons learnt, as noted by the project team, during the delivery of the phase 2 LOOP demonstration.

Table 19 - Demonstration project lessons learnt

No.	Outcome	Description (what happened?)	Impact	Benefit (What will we do on future schemes)
1	Opportunity	The number and timing of deliverables has caused issues with invoicing. The project was designed in this way so that money was available on a monthly basis. In hindsight this was an incorrect strategy.	Late Invoicing impacting on overall cash flow.	Fewer written deliverables that are spaced further apart within the project plan. Ensure project team have enough time to gather evidence together.
2	Opportunity	Throughout the project we have struggled to maintain a good level of understanding with contractors. On occasions the on site delivery has aligned to the requirements of the capital programme, a known context for our contractor, rather than the immediate needs of the innovation project (ref. item 3 below)	Programme delays	Utilise more regular feedback session with Contractor in the calendar & more time with MSP framework team.
3	Opportunity	Contractor waited for exact design details to be available ahead of ordering made to measure pipework.	Programme delays	Insist on contractor bringing additional materials to site to enable easy adaption to design changes or issues. Also insist on early installation of main pipework runs and checking of falls etc. More flexibility required.
4	Win	Overestimated contractor input, particularly materials, based on assumptions concerned with pipework requirements and civil engineering. Some of these estimated costs would normally be included within a risk allowance.	Underspend	Include an allowance for risk within future projects (not allowed within the rules of the DESNZ project).
5	Win	Biogas successfully introduced into LOOP system - UU & Levidian teams navigated new territory regarding innovation & DSEAR regs to enable this to happen. Great team that were willing to solve problems rather than avoiding them.	Successful Technical Delivery	Refer to the knowledge and experience gained through the delivery of this project.
6	Opportunity	Alignment of a new technology with the requirements of our existing design processes called for more specialist and detailed resources to be engaged on the project.	Resource requirements	Add updated guidance to our project delivery process so we can be more efficient in the future with regards to getting through the DSEAR and Ex equipment requirements.
7	Opportunity	We experienced a couple of near misses that could have been avoided (electrical installation / commissioning and pipework leaks)	Health & Safety	More focus on site activities in the future to avoid any near misses. Additional processes have been implemented on this trial to aid this moving forwards.
8	Opportunity	Although MBC presented the best technical option for the delivery of the LOOP demonstration (availability of both biogas and biomethane) it is the largest UU biogas site with high levels of regulation and site specific requirements (COMAH).	Technical and Operational Complexity	Future consideration around site selection and how we determine the best site. Work with strategy and operational teams to determine the best / safest / easiest site that meets with requirements.
9	Opportunity	By moving the LOOP from Levidian to site early we have incurred significant additional site hours to complete commissioning tasks.	Increased site work	Ensure that manufacture and dry commissioning is completed at Levidian HQ to reduce input while on site.

9.0 Conclusions and Next Steps

Successes

The LOOP100H demonstration plant at MBC has been successfully delivered, achieving a series of key technical and strategic milestones:

- **FOAK (First of a kind):** This is the UK's first example of hydrogen production from sewage waste, a truly innovative project that's pushing the boundaries of wastewater resource recovery.
- **Scaling:** The LOOP system has been successfully scaled up to the LOOP100H model.
- **Feedstock Flexibility:** LOOP has demonstrated the ability to process wastewater-derived biogas from an anaerobic digestion plant.
- **Graphene Production:** LOOP effectively converts methane, comprising 60% of the feedstock gas, into functional graphene.
- **Hydrogen Extraction:** A yield of 50% hydrogen has been successfully extracted from biogas, providing a clean fuel source and adding value to the process output.
- **Operational Learning:** The site team has developed a detailed understanding of the enabling works required for future LOOP installations.
- **Carbon Impact:** Preliminary carbon assessment data (available at the time of writing) indicates that the current LOOP configuration results in total emissions of 140.39 $gCO_2eq/MJLHV$, exceeding the threshold for the UK LCHS. However, there are three key improvements that can be made to the carbon intensity: use of renewable energy in the electricity supply; switching the inert gas used for purging to nitrogen; and allocating feedstock emissions by energy. Implementing these measures would result in an emissions factor of 12.97 gCO2e/MJ LJV H2, comfortably below the threshold set out by LCHS.

Key Barriers

- **Regulatory complexity:** Although MBC presented the best technical option for the delivery of the LOOP demonstration (availability of both biogas and biomethane), it is the largest UU biogas site with high levels of regulation and site-specific requirements (COMAH) which added complexity to the project.
- **Biogas moisture content:** The biogas feedstock includes more water than anticipated which means that filters and pipework within the LOOP system need to be replaced more regularly than normal. This can be addressed by the installation of moisture removal systems upstream of the process units but should be considered a high risk on biogas sites and extra precautions taken.
- **Familiarity with microwave and plasma systems:** The introduction of microwave and plasma technology represented a new and unfamiliar process for UU. To overcome this, the project team proactively invested in training and knowledge-sharing to build understanding across the site, safety, and project teams.

Next Steps

A further month of operation has been agreed with DESNZ which falls outside of the reporting window for our final report (March 2025). The additional month will allow the project team to increase confidence levels regarding the capability and functionality of the LOOP100H. We are specifically looking at the yields of graphene and hydrogen from the LOOP and how these impact the carbon assessment and commercialisations plans.

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