Project Name – The sustainable biogas, graphene and hydrogen LOOP – Phase 1

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1. Introduction

The Department for Business Energy and Industrial Strategy (BEIS) has provided a total of £5 million in funding to support innovation in hydrogen BECCS (bioenergy with carbon capture and storage) technologies. United Utilities (UU), in partnership with Levidian, were awarded Phase 1 funding for the Levidian LOOP technology from the Hydrogen BECCS Innovation Programme.

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 will investigate and design the use of a LOOP for the conversion of methane to graphene and hydrogen using a fully sustainable biogas feed source from a United Utilities sludge treatment system.

2. Science and Engineering

2.1 Science behind LOOP process

The innovative LOOP process directly breaks down the chemical bonds of methane 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 as long as 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 the reactor 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 much more energy efficient than 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 reactor to extreme temperatures. The process also works optimally at near ambient pressures since the energy comes from the microwaves not the conditions of the reactor system. Like plasma torches, microwave sources can be powered by electricity, making the process portable, and zero carbon when powered by renewables. A first-generation LOOP device (capable of cracking 1.5m^3/h of natural gas) has been 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. However, to support hydrogen BECCS commercialisation, we are aiming to develop an engineering design for a larger scale LOOP device with an integrated hydrogen separation module, capable of processing biogas (and biomethane) 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 phase 2 testing of a LOOP100 demonstrator has the potential to prevent emission of over 200 tonnes CO_{2eq} and roll out of LOOP devices across UU’s 15 wastewater treatment sites could provide 42MW of low carbon hydrogen capacity through transformation of 35,000 tonnes per year of biomethane generated from sludge treatment. As a critical part of this Phase 1 feasibility study, we sought to undertake a series of laboratory trials to assess whether biogas (a mixture of methane and carbon dioxide) can be utilised as an alternative feedstock to biomethane or natural gas in LOOP operations. Key concerns that needed to be addressed during the project were the ability to sustain a stable plasma within the reactor, plus the quality and yield of the hydrogen and graphene products being generated.

2.2 Biogas Testing at Levidian Technology Centre

2.2.1 Analysis of biogas composition

Biogas generated at United Utilities facilities in NW England is routinely sampled to analyse and monitor the gas composition. Historic data indicates that biogas that has been dried and passed through a carbon filtration step typically consists of 60-65% methane and 35-40% carbon dioxide, with only trace amounts of nitrogen, oxygen, and higher hydrocarbons. As part of this feasibility study, on 04 November 2022 Element Materials Technology Environmental UK Ltd collected samples of both biogas and biomethane from UU's Davyhulme MBC site. Laboratory analysis of these samples was carried out by Marchwood Scientific Services Limited and bulk gas analysis results are disclosed in Table 2.2.

Table 2.2: Bulk gas composition - samples of biogas/biomethane collected from Davyhulme

Biogas			Biomethane	
Gas type	**Concentration**		**Gas type**	**Concentration**
Methane	63.2%		Methane	98.5%
Carbon dioxide	36.4%		Carbon Dioxide	1.2%
Oxygen	0.4%		Oxygen	0.3%
Nitrogen	0.0%		Nitrogen	0.0%
Hydrogen sulfide	3 ppmv		Hydrogen sulfide	1 ppmv

2.2.2 Biogas samples and experiments

It had been our original intention to collect up to 5 samples of compressed biogas (25-50 m^3) from several United Utilities sites in NW England to utilise as feedstock for Levidian's R&D plasma reactor - the aim being to assess the impact of CO_2 content on graphene and hydrogen production yields. However, during the early stages of the project it became evident that the collection of compressed biogas samples would be far more complicated than initially envisaged. Health and Safety considerations meant that there was insufficient time within the project for specialist gas handlers to perform sampling of the required samples of compressed biogas. An alternative approach was initiated which involved the procurement of cylinders of compressed methane and carbon dioxide to generate samples of synthetic biogas.

An existing Levidian LOOP plasma system was repurposed to accept the synthetic biogas mixtures to be tested. The reactor setup included the same production nozzle and hardware used for G3 graphene production from natural gas. Feed gas supply was taken from separate high purity methane and carbon dioxide gas bottles and blended in a controlled manner using precision mass flow controllers. The mass flow controllers allowed the total flow rate to be modified whilst keeping percentage gas composition through the nozzle constant and also enabled modification of the ratio of CH_4:CO_2.

Performance metrics monitored during the experiments focused on:

- Plasma stability over extended periods – can the plasma state continue stably and predictably without excessive operator intervention?
- Overall system condition – do equipment temperatures, pressures and component wear fall within working limits?
- Characterising output products (yields) – does the system process this biogas blend effectively into other useful products and what are they? What is the yield of solid carbon achievable?
- Characterising output products (quality) – Can any solid carbon produced be considered graphene and of what quality? What is the exhaust gas composition and initial quantification of hydrogen yield?

Firstly, a biogas equivalent blend of 65% methane + 35% CO2 was tested at a total flow rate known to be stable and optimal when running on pure natural gas. After the correct tuning of the system, this experiment ran stably for multiple hours without issue. The plasma remained stable throughout and the system was stopped manually. Pressures and temperatures during the run were well within acceptable limits and upon opening the system we found that solid carbon had been produced.

The yield of solid carbon was significantly lower than when compared to a pure natural gas or biomethane feedstock at the same flowrate (around 10% by weight), however this can be partially attributed to the lower carbon content of the incoming gas stream and to the fact that oxygen is present in the plasma. In the presence of oxygen, the carbon appears to favourably combine with oxygen to form carbon monoxide, rather than forming solid graphene.

Raman analysis of the graphene, provided in Annex A, showed the prominent G-peak associated with ordered graphene and graphitic materials, as well as a high 2D-peak which suggests few layer graphene flakes (2-10 layers) are present similar to our G3 grade material. The D-peak, usually associated with defects in the graphene sheet is particularly high for this material, and after some basic hydrophobicity tests we concluded there is a strong possibility that this is not necessarily due to sheet defects but rather oxygen-containing functional groups on the graphene's surface. This is a very interesting finding, as it suggests that using a carbon dioxide containing biogas can produce a ready-to-use functionalised graphene material which has been functionalised *in situ,* not requiring any additional post-processing.

Analysis of the exhaust gases by real time quantitative mass spectrometry showed that the bulk of the gas consisted of hydrogen, with the secondary component being carbon monoxide. Acetylene was present in small amounts, but a few percent of carbon dioxide and methane still remained. Using knowledge of our other systems we decided to reduce total flow rate through the nozzle, to increase gas retention time in the plasma zone and improve the chances of cracking the remaining CO_2 & CH_4.

Running at a reduced total flow rate (64% of original) but retaining the same 65/35 CH_4/CO_2 split yielded successful results, reducing residual CO_2 & CH_4 in the exhaust gas to fractions of a percent, whilst maximising the conversion to hydrogen, carbon monoxide and acetylene. Solid carbon yield was down slightly but actually showed a marginal increase when expressed as the percentage of carbon input that is extracted as solid carbon.

This experiment also ran for multiple hours with one minor trip, possibly suggesting slightly reduced plasma stability at the lower gas flow rate. Multiple experimental factors can affect the ability to sustain a stable plasma within the reactor, however, preliminary experiments give the team confidence that stable plasmas using biogas can be maintained over prolonged periods of time. Raman analysis showed the graphene quality was in fact improved and a higher 2D-peak indicated the presence of few layer graphene (1-3 layers), closer to our G1 high grade material (Annex A).

The hydrogen rich exhaust gas with a significant percentage of carbon monoxide can be considered a "syngas" which presents an alternative avenue for monetisation of the output of LOOP running on biogas. Hydrogen can be separated out from the other gas components and purified as detailed below or alternatively, this syngas blend could be used for additional processing. Carbon monoxide presents a more reactive precursor molecule when compared to inert CO_2, which can be readily reacted to form high-value chemicals. Syngas can also be used as a fuel, replacing natural gas.

Supplementary experimentation then began by decreasing the CO_2 content of the input gas to 25%, with CH_4 making up the balance, whilst fixing flow rate at the original higher flow. This experiment ran stably for over an hour before the plasma became unstable. Exhaust gas analysis showed that residual CH_4 & CO_2 remained at a similar level as the first experiment. With the higher percentage of hydrogen-containing methane and lower percentage of oxygen containing CO_2 in the incoming gas flow, the amount of hydrogen & acetylene in the exhaust gas increased whilst carbon monoxide content decreased.

This helped to confirm that there is a somewhat predictable relationship between the ratio of incoming CH_4/CO_2 ratio and the amount of hydrogen, acetylene & carbon monoxide expected in the exhaust – higher concentrations of methane should boost hydrogen production rates.

Our feasibility experiments have demonstrated that the LOOP process successfully transforms biogas into a high grade of graphene and up to 90% of the hydrogen present in the input gas is converted into hydrogen gas. The establishment of an upper limit to the nozzle flow rate required for decomposition of virtually all CO_2 & CH_4 to other molecules was also a key takeaway.

2.3 Hydrogen Purification

One of the key objectives of this feasibility project is to identify a suitable system for upgrading the purity of the hydrogen gas output from LOOP. Historic data has shown that hydrogen is the major component of the exhaust gas, but H_2 content is typically 60-70% v/v with the balance being a mixture of hydrocarbons including methane and acetylene. Whilst this hydrogen rich blend can be used directly for on-site heat or power generation, high purity hydrogen (>99.99% v/v) has a wider range of potential applications including fuel cells and hydrogen ready engines/turbines. Production of high purity hydrogen requires separation, compression, and storage/transportation.

2.3.1 Hydrogen Separation

Broadly speaking, hydrogen separation technologies can be classified as either pressure swing adsorption (PSA) or membrane-based processes. Organisations such as Linde and Air Products have been developing PSA systems for over 40 years and together, they have installed 700 PSA plants globally. These large-scale systems for hydrogen purification are primarily integrated into steam methane reforming plants and can handle feed gas flow rates in the range 1,000 - 120,000 Nm^3/h. The proposed LOOP phase 2 demonstrator will require processing of a much lower feed gas flow rate of 20 – 25 Nm^3/h and finding a provider of scaled down PSA equipment for hydrogen purification has proven challenging. The target specification for hydrogen purity is 99.99% v/v and the hydrogen recovery rate from the separator should be at least 80%.

A range of H_2-permeable membranes have been developed that can remove CO, CO_2, N_2, CH_4 and H_2O from gas streams e.g., PRISM® hollow fibre membrane separators (Air Products) and HISELECT® gas separation membranes (Evonik/Linde). Whilst membranes can potentially be used as a standalone purification method, they are gaining more attention when used in combination with PSA systems to deliver customised hybrid solutions.

During this project, we have held discussions with several hydrogen purification system providers and the pros and cons of the different technologies are summarised in Table 2.3.

Table 2.3: Comparison of alternative hydrogen purification technologies

Technology	Electrochemical hydrogen purification and compression (Pt membranes)	Vacuum assisted PSA (vPSA)	Palladium membrane hydrogen gas purifiers
Pros	• Combined H_2 purification and compression. • Proven tech for H_2 compression. • Equipment footprint meets LOOP requirements.	• PSA proven tech for H_2 separation. • vPSA systems for up to 1000 Nm^3/h gas flow. • Specialist absorbents available • Equipment footprint meets LNS requirements	• Extremely high purity of H_2 achieved • Impurities removed to <1 ppb • Small device footprint • Series of devices capable of processing 0.3-81.2 Nm^3/h
Cons	• Sulfur impurities in gas stream not tolerated. • CO in gas stream may inhibit Pt catalyst. • Acetylene in exhaust gas may react with H_2. • Limited demonstration of purification element.	• No compression of purified hydrogen – additional equipment needed for this.	• Expensive – smallest systems start at around $10,000 with larger system costing up to $500,000 • Operating temperature >350°C • Separates pure H_2 from source gas with ppm or % level impurities

After carrying out extensive technical due diligence, it was decided that the vacuum assisted pressure swing adsorption solution met all our requirements and will be the hydrogen separation module in the proposed phase 2 demonstrator unit. A quotation has been received for a 4 bed vPSA hydrogen separator. The use of biogas in place of natural gas as a feedstock for the LOOP process has been shown to result in elevated quantities of carbon monoxide in the exhaust gas. It is envisaged that this will not have a major impact on the performance of the vPSA hydrogen purification module, if hydrogen purity and recovery rates are affected, the type of absorbent material used in the system will be modified.

2.3.2 Hydrogen Compression

As a fuel, hydrogen has the highest energy content per kilogram. Unfortunately, the density of hydrogen at atmospheric temperature and pressure is only 90g/m^3 meaning that efficient compression of hydrogen to >250 bar pressure is necessary. There are two primary compression methods used for hydrogen: 1) Positive displacement e.g., reciprocating compression (where a piston compresses the gas) and 2) Dynamic e.g., centrifugal type turbo compressor.

Three providers of H2 compression technology have been shortlisted, based on their ability to provide a system capable of handling the relatively low volume flow rates from our LOOP demonstrator and compress hydrogen to a minimum of 250bar.

- PureH2 compressor system (Pure Energy Centre – UK) prices start at £40,000
- Hurricane and 6000 Series compressors (Sauer Compressors – UK)
- Electrochemical Compression (HyET – Netherlands)

2.3.3 Hydrogen Storage

As part of this feasibility study, consideration is also given to the storage of the quantities of hydrogen produced during the 1000 hours of demonstrator testing that will be carried out in the proposed Phase 2 project. Hydrogen can be stored either physically, in gas or liquid form, or chemically using metal hydrides, adsorption materials and reformed organic fuels such as methanol and ammonia. For our demonstration project, storage of hydrogen as a compressed gas is considered the simplest option but will require the use of pressurised vessel or tanks. Storing hydrogen at higher pressures, increases its volumetric density and necessitates the use of smaller storage vessels. However, COMAH regulations mean that during the phase 2 demonstration, the quantity of hydrogen stored on UU's site will need to be limited and uses for the hydrogen being produced in the project will need to be established. According to Hydrogen UK, hydrogen storage costs are currently around £12/kWh, equating to roughly £400/Kg of hydrogen. This means that storing 100Kg of hydrogen in tanks or cylinders at pressures greater than 500bar is likely to cost £40,000. Three potential on-site uses of hydrogen have been identified at UU's Manchester Bioresources Centre at Davyhulme:

1. Hydrogen fed into anaerobic digestors to boost biogas productivity
2. Blend hydrogen with biogas currently being used to power site steam boilers and combined heat and power (CHP) systems
3. Demo suitability to power a hydrogen fuel cell generator e.g., HYMERA by BOC

Additionally, choosing to locate the demonstrator in Northwest England, we find ourselves in close proximity to several hydrogen infrastructure projects (HyNET NW hydrogen pipeline and Trafford Green Hydrogen) that could act as potential off takers for the hydrogen we produce.

3. Carbon Life Cycle Assessment

As per industry standard 'Carbon Management in Infrastructure PAS2080' (BSI, 2022) there are four major life cycle stages. Each of these is split down into modules as follows:

- Product stage (also known as 'cradle to gate') (modules A1-A3)
- Construction process stage (modules A4 & A5)
- Use stage (modules B1-B7)
- End of life stage (modules C1-C4)

- There is an additional stage beyond the life cycle of the asset that is intended to provide a broader view of its environmental impacts: Benefits and loads beyond the system boundary (module D)

In line with PAS2080, this LCA therefore aimed to include: material extraction (module A1), transport to manufacturer (A2), manufacturing (A3), transport to site (A4), construction (A5), use phase (B1, e.g. concrete carbonation but excluding operational carbon), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), deconstruction (C1), transport to end of life facilities (C2), processing (C3) and disposal (C4). However – the B1-B8 lifecycle modules were calculated separately to this infrastructure study as they form the separate modules of the hydrogen gas production analysis by a LOOP1000 unit. Figure 3.1 shows the boundaries of the 3 calculations completed in this phase 1 study.

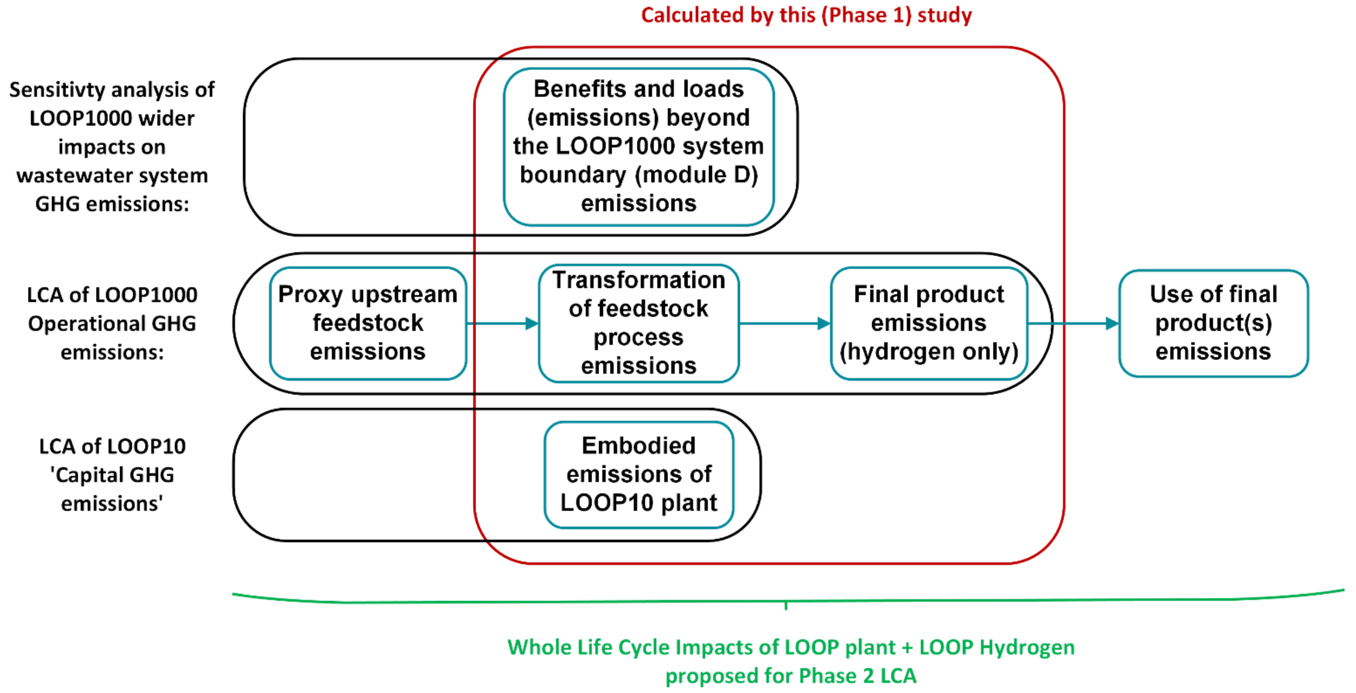


Figure 3.1 Boundary and scope definition outlining the three separate calculations (left) completed by this Phase 1 study

The outcome of this study is a sensitivity analysis of the wider impacts of LOOP on wastewater treatment works and two LCA studies. Due to the data available at the time of calculation results are presented for different sizes of LOOP plant. Therefore, LOOP10 refers to the pilot plant developed by Levidian. LOOP1000 refers to the larger scale theoretical system that is proposed by Levidian for post-Phase 2 deployment.

The embodied emissions associated with the LOOP10 unit were calculated within LCA software 'eToolLCD' and the results are presented in the 'Embodied' tab of the spreadsheet model (Annex B). This software uses industry standard emission factors and methodology and is also IMPACT compliant (BRE, 2022). Key assumptions can be found in the full LCA report in Annex B.

The studies and key results are shown in Table 3.1.

Table 3.1 Summary of the key studies undertaken as part of this work and key results

Study	Description	Functional unit	Key results
Infrastructure LCA (LOOP10)	The embodied 'capital' GHG emissions associated with a LOOP10 plant	$kgCO_2e/kW$ of LOOP system	A single LOOP10 unit is estimated to have embodied 'Capital carbon emissions' (non-Use phase) of 10.7 tCO_2e/unit.

Hydrogen production LCA (LOOP1000)	The GHG emissions associated with producing a certain quantity of hydrogen in a LOOP1000 system	$gCO2e/MJ_{LHV}$ of hydrogen (as per UK Low Carbon Hydrogen Standard)	LOOP1000 is expected to produce Hydrogen with a carbon intensity of -0.2 gCO_2e/MJ_{LHV} H_2

Considering the wider system impacts (Module D), carbon related impacts/benefits include the use of hydrogen and carbon-based products, as well as the impacts of diverting biogas produced on site to LOOP style hydrogen production. Almost all biogas produced by UU is already beneficially used, therefore diversion of biogas or biomethane through the LOOP process will result in trade-offs in the wider system. An additional assessment was conducted at a high-level to compare existing biogas end use against the LOOP alternative biogas use. However, not enough data was available for incorporation with the other two 'full' LCA studies (above).

A high-level model was constructed to estimate these impacts. This was based on UU's Manchester Bioresources Centre (MBC), which is a large sludge treatment centre operating thermal hydrolysis. It was assumed that hydrogen produced by LOOP1000 would be injected into the gas grid.

A range of scenarios were tested, each with various proportion of biogas used for MBC BAU and several scenarios incorporating LOOP. The results show that for 3 of the 4 scenarios modelled, there would be a net carbon benefit from using a LOOP1000 unit. Full details of the scenarios used and the results can be found in the full LCA report in Annex B.

The process feedstock to the LOOP system is biogas. This biogas is produced solely from anaerobic digestion of sewage sludge and using this biogas will not result in land use change.

4. Social Value Assessment

Social value is a way of quantifying how different interventions affect people's lives, primarily focusing towards the impact on people's quality of life. The typical components of social value include; community wellbeing, equality and equity, housing, mobility, work, physical and mental health, and access to vital services. As part of Phase 1 of the LOOP project, UU, Levidian and Jacobs made a set of commitments to delivering social value outcomes. These are detailed in Table 4.1. The key Phase 2 planning stages are set out in Table 4.2.

Table 4.1 - Phase 1 key social value commitments:

Commitment(s)	Action(s)	Result(s)
Levidian to deliver a summer internship placement	Levidian took on one student for 4 weeks in summer 2022, to work on project delivery centred on the BEIS Hydrogen BECCS Innovation programme.	At the end of the placement, the student undertook a Question & Answer session to document his experience, including the key skills he gained and how he will utilise these skills in his future career.
To provide e-mentoring to students from disadvantaged backgrounds To provide 1 mentor per 10 FTEs on the project	UU delivered 2 hours of mentoring to two interns, and 4 hours of mentoring to UU graduates. Two team members signed up as mentors to the Social Mobility Foundation's Aspiring Professionals Programme. Rebecca (Jacobs) provided mentoring to another team member who has recently transitioned into the industry.	E-mentoring helped to highlight the career prospects and learning opportunities that are available to the mentees, therefore encouraging the take up of STEM jobs in green skill sectors.

To volunteer by engaging with colleges and universities, in addition to attending careers fairs to encourage the uptake of careers in this area.	Lisa Mansell (UU), engaged with a school in Merseyside to share her experience being a female in engineering. Levidian are working to increase their presence in the local area and develop partnerships with local schools and colleges.	Exposure to engineering careers for students that may not otherwise have even considered that this was attainable to them.
To support economic growth and business creation in the local area by reviewing the pipeline of procurement opportunities and mapping these against local capabilities.	Levidian has signed a Memorandum of Understanding (MoU) with Specialised Management Services Limited (SMS), which sets out a pathway for collaboration. Levidian has established an on-site workshop for fabrication of key reactor components and have recruited a team of local talent to work there.	SMS will be responsible for the fabrication of larger LOOP devices (LOOP50 scale and beyond) and have the capability to construct the plasma reactor chambers for Levidian (currently these are fabricated in Poland). Jobs provided for local talent.
Jacobs supplier diversity and inclusion team to support the development of a responsible procurement process for the project. To pay all employees the Real Living Wage and ensuring compliance with the supply chain to the UK Modern Slavery Act.	All partners undertook a review of their terms and conditions in line with this ambition. Jacobs supported Levidian to develop their responsible procurement policies further by sharing their Supplier Code of Conduct.	Levidian are currently developing their corporate social responsibility procedure, including statements on whistleblowing, anti-bribery and corruption, Occupational Health and Safety, Human Rights, Modern Slavery, and People and Culture which considers diversity, disabilities etc.

Table 4.2 - Phase 2 plan key stages:

Phase 2 stages	Why is this important?	Relevant actions / research
Understand community needs	Crucial for understanding the local context in which a project or company operates. Identifies social, economic, and environmental opportunities and challenges in an area as well as identifying current resources and recognising resource gaps.	The 2 main project locations are Cambridge (Levidian) and Greater Manchester (UU). The community needs assessment will focus on both areas. The 2019 Index of Multiple Deprivation (IMD) indicates that in Greater Manchester 39.4% of people live within a neighbourhood ranked among the most deprived 20% of neighbourhoods in England. In Cambridge only 3.7% of people live within the 20% most deprived neighbourhoods.
Identify and engage with stakeholders	Generating value in the right place and for the right groups. Enabling decision makers to challenge assumptions and ensuring that solutions create a sense of shared ownership. Engaging with the community to identify local needs strengthens relationships and builds long lasting social value.	Initial stakeholders include: • Universities • Schools/colleges • Government organisations • Supply chains and local businesses • Users of technology • Local residents.
Map opportunities for value creation by	A theory of change is an illustration of how an intervention is expected to	During Phase 1, a workshop was held to establish the vision and

developing a theory of change	lead to change or desired outcomes. Developing a Theory of Change prior to undertaking any social valuation allows for a better understanding of the activities that generate social value. To create a theory of change, inputs are mapped on to immediate outputs, then onto the consequences of these outputs, and finally the effects that these outcomes would have on society (impacts). Following this process leads to a better understanding of the link between activities and desired impacts and the steps required to evaluate then value these impacts.	aspirations for delivering social value during Phase 2. Social value opportunities, were identified for each of the following four capitals: • Human capital • Natural capital • Produced capital • Social capital
Establish measures, data points and targets to assess progress against commitments	The development of a set of measures and data points helps to monitor and evaluate progress against the commitments made. If the desired outcomes are not being generated, the theory of change can be revisited to understand what additional action needs to be undertaken.	An updated set of commitments for Phase 2 has been developed based on our understanding of the community, conversations with key stakeholders and workshops to develop the social value aspiration. See the full report in Annex C for the full list of measures.

5. Engineering Design

The design of the LOOP system during phase 1 has consisted of two parts

1. The upscaling of the LOOP system
2. The enabling works to allow installation within an existing 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.

5.1 Upscaling of the LOOP and incorporation of hydrogen production

The detailed LOOP100H P&ID with Process Flow Integration is included in Annex A-100186-1 LOOP100H. Our proposed demonstrator design consists of the following main subsystems: cooling, argon feed, methane feed, 5 x LOOP reactor modules, H_2 separator, graphene collection. The LOOP100H design is based on a modular system, with the basic LOOP reactor 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 a standard, 40ft shipping container for easy transportation. This is the second layer of the modular system, as the individual containers can be then combined, stacked on top of each other, thus creating more powerful LOOP systems.

The proposed system will be fully automatic, requiring no human supervision. The logic is controlled by an industrial CPU. All process data will be 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 goes into emergency mode.

Graphene collection system will also be 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 will have a full overview of all process parameters, the current state of the LOOP and can visually assess the situation through access to the built-in CCTV system. All this is possible through wireless communication, thanks to the use of GSM modules that will be installed inside the LOOP.

LOOP is designed to meet all ATEX/UKCA certification requirements. An internal safety gas system independently controls key safety parameters such as LEL of H_2, CH_4 and 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. Connecting LOOP to external infrastructure and its placement is very simple. In the case of LOOP100H, the container can be placed on flat, paved ground, and connected to site utilities using one 125A 3P+N+E 415V cable and one biogas/biomethane source pipe. The LOOP design has been optimised in such a way that over 90% of all system components are standard (off the shelf), widely available on the market.

5.2 Manchester Bioresources Centre (MBC) Enabling Works

To incorporate a trial of the LOOP within an existing biogas processing facility we have needed to understand a broad range of risks regarding technical, commercial, regulatory and environmental concerns. UU operate 14 biogas producing and processing facilities in the North-West England. Of these facilities the Manchester Bioresources Centre (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 with regard to explosive atmospheres and gas storage that would need to be overcome. Through discussions with the MBC site operations team and technical experts our LOOP project team have successfully identified a location that mitigates these risks and also limits required interactions with daily operating procedures at MBC.

5.2.1 Location for LOOP at MBC

5.2.1.1 Potential MBC Locations

There are three locations available for the installation of LOOP at MBC as shown in the potential locations photograph in Annex A.

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

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. The outcome of the location review is summarised in the selection matrix table in Annex A. The IDR report is also included in Annex A of this report.

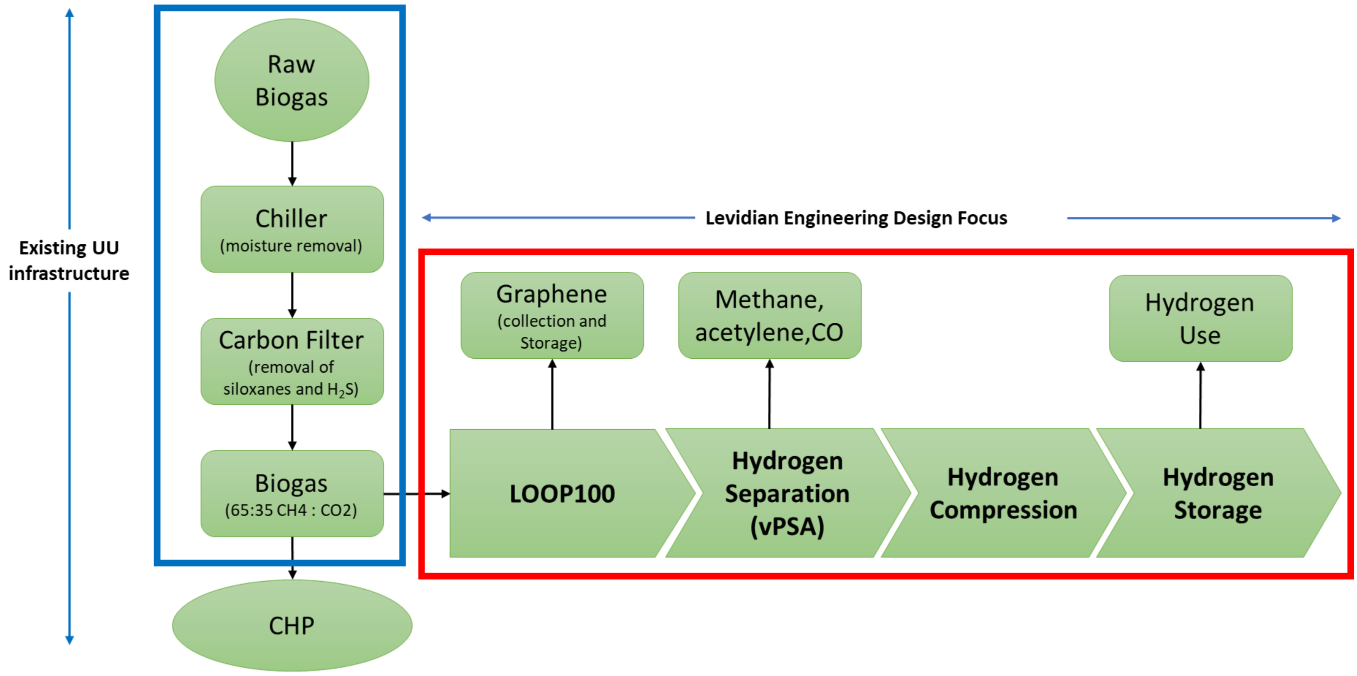
5.2.1.2 Location 3

Our recommended location for the LOOP is Location 3. This provides us with a working area outside of 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 have agreed that this represents a suitable mitigation against the disadvantages provided by locations 1 and 2 regarding explosive atmospheres and restricted access. Location 3 also provides more straight forward access to a supply of biomethane if we find the trial should move to a higher methane content feed substrate.

5.2.2 Interfacing with the existing site

At MBC UU produce two forms of biogas that are of potential use for LOOP.

- Biogas most similar to the wider UU biogas generating assets on other sites. This has an approximate methane content of 60%, 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.



- Biogas that has been through clean up processes over and above those mentioned above such that it has a suitable methane content (>95%) for injection into the natural gas grid as Biomethane. 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 impacts on the LOOP processing capability as this provides the most benefit to UU and wider biogas producing industries.

5.2.3 LOOP Connection Points

5.2.3.1 Biogas Feed

With reference to Annex A (Location 3 Pipework, cabling and connections) the LOOP container will be positioned on an existing tarmac site road to the North of the gas to grid processing area. Biogas will be supplied via an existing 2" (50mm) connection downstream of the gas to grid carbon filters. The purple supply pipe shown in the photograph (80m) will transfer the biogas to the LOOP at a rate of 15 m^3/hr. The pressure at the point within the existing process is approximately 100 mbar. For the LOOP to operate correctly this will need to be increased to a minimum of 1 bar. This will be done by passing the feed biogas through a pressurisation system upstream of the LOOP. This pressurisation system, due to the location of LOOP outside of the immediate MBC operational area, will be electrically operated, with a supply from the LOOP container, but will not be ATEX rated and will therefore need to be operational outside of the container.

5.2.3.2 Biogas and Syngas (hydrogen / carbon monoxide) discharge

The LOOP designed for MBC will have two gas discharge streams, a waste biogas that has not been altered in the first pass through the LOOP and a hydrogen / carbon monoxide syngas. In our design we plan to blend the two stream and discharge them, via the green line in the photograph, to the main biogas pipework that takes biogas from the existing anaerobic digestion tanks to the gas storage bags at MBC. By doing this we are removing the need to store our gas separately and the safety implications of doing that. As the gases discharged by the LOOP are low with regard to flow (15 m^3/hr into a gas flow of 3000 m^3/hr) and high with regard to pressure (1 bar into <100 mbar) this design option provides us with the most practical and efficient means of completing the gas flow to, through and from the LOOP whilst also avoiding the need for additional equipment. The discharge pipework from the LOOP to the biogas main will be manufactured from 316SS at an approximate distance of 27m and diameter of 2” (50mm). This will include a suitable pipework arrangement that maintains operational capability to attach further instrumentation or venting equipment via a 2” valved blank connection (as already in place). These return flows will also be regulated to maintain a positive pressure against the biogas within the main pipeline to the biogas storage area. A non-return check valve will also be provided to ensure biogas does not flow up the LOOP discharge pipework.

5.2.3.3 Power Supply

The LOOP requires a 125-amp 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 are able to run an 80m supply cable, above ground on cable trays, from the existing MBC Gas to Grid Motor Control Centre (MCC) (UU Asset MC17-001) to the LOOP mains supply panel. We have identified a spare compartment (Compartment 8A) within this MCC which will need to be equipped with a 200 amp busbars and associated fuse switchgear.

1.2.3.4 Control Instrumentation from UU

We have identified the following signals as being required from the existing MBC control system to enable the LOOP to align to site safety requirements and ensure a safe shutdown as and when required.

- Low level from gas bags (for interlock with LOOP shutdown)
- Low pressure switch (for interlock with LOOP shutdown)
- Fire / alarm / emergency signal for shutdown

The signals will be provided by UU to the LOOP system where they will be configured during commissioning to implement the required operational controls.

1.2.3.5 Connectivity

The LOOP operations team will require remote access to the LOOP control system. This will be provided by connectivity within the LOOP control panel. The LOOP will therefore be a stand alone system not requiring a wired or wifi internet connection from the main UU site.

1.2.3.6 Dangerous Substances and Explosive Atmospheres Regulations (DSEAR)

As an organisation that operates several biogas generating facilities UU are required to adhere to the DSEAR regulations. UU have a specific set of guidelines and task/documentation that need to be completed to the satisfaction of our DSEAR team in order for processes to be installed and operated. The LOOP will be subject to securing this authorisation, however, the details required by the UU DSEAR team will only be available during manufacturing and site inspection which occur during phase 2 of the LOOP development for MBC. Phase 1 can therefore only be concerned with understanding what those requirements are and allow time for them to be completed within the project programme.

There are 25 documents in total that make up the required information for DSEAR assessment. The complete list is provided in Annex D. Some of these documents will not be relevant to the LOOP installation and operation at MBC. For each piece of equipment detailed in the Ex register (UU Document AST1006) the following should be submitted:

- 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
- I.S circuit loop calculations (where applicable)
- I.S circuit loop drawing (where applicable)
- Any other verification documentation deemed necessary by the UU DSEAR team, e.g., manufacturing information / calibration certificates / preservation / etc. This may be dependent on the particular work being completed or type of equipment installed.

6. Commissioning and Testing Plan

6.1 Functional Testing

LOOP100H will be built based on an approved CAD model meeting ATEX/UKCA requirements. The finished system will first pass the Factory Acceptance Test (FAT). An example of a detailed test performed on a single LOOP module (demo) is presented in the “LOOP100 – FAT” document, Annex E. During this test, individual sections of each subsystem are checked, then each subsystem is tested separately, and finally the entire LOOP with auto mode.

After the LOOP is delivered to its destination, an additional Site Acceptance Test (SAT) will be conducted. This is a very similar procedure to the FAT, except for a few additional points that verify the readiness of the external infrastructure and further site-specific safety requirements.

The next step is to perform the first full system boot in auto mode. At this stage, the stability of the system will be assessed, and the following parameters tested: composition of inlet and outlet gases, purity of produced hydrogen, quality, and yield of produced graphene.

UU personnel will then be trained to deal with the basic operation of the LOOP system. Since the system is fully automatic, this is mainly limited to preventive maintenance, described in “LOOP maintenance schedule”. Examples of two SOPs describing basic maintenance activities are included in “LOOP SOP 8 - Smoke Detector Test” and “LOOP SOP 11 - Air Filters” (Annex E). Basic maintenance will be performed by trained operators at UU’s Manchester Bioresources Centre, whilst additional support and regular inspections will be carried out by the Levidian service team.

All process data is stored in a cloud database, which the Levidian team will have easy access to – enabling regular analysis of all critical LOOP operating parameters. Furthermore, at the end of the testing period, another SAT procedure will be performed. These two activities will allow us to identify any deterioration in performance over the demonstrator testing period.

6.2 Performance Testing

To meet BEIS’ expectations regarding performance testing of the proposed Phase 2 LOOP100H demonstrator system, the following data will be collected during the on-site trials at UU’s Davyhulme wastewater treatment works.

- Number of operating hours during trials (minimum 1,000 hours during 6-month testing window)
- Number of continuous operating hours (aim to demonstrate over 48 hours of continuous operation of LOOP system)
- Record of number of hours of system downtime resulting from planned or unplanned maintenance.
- Documented findings from any root cause investigations into equipment or component failure during testing period.
- List of all LOOP consumables used during testing programme
- Daily log of biogas consumption (monitored using mass flow controllers - target: min. $10m^3/h$)
- Daily log of electricity consumption due to LOOP operation

- Daily analysis of LOOP exhaust gas composition monitored using in-line hydrogen gas sensor (target specification: > 55%vol hydrogen)
- Daily analysis of hydrogen production rate using mass flow controller – target minimum 500Kg hydrogen from 1,000 hours of testing (assume biogas with 65%vol methane content)
- Daily analysis of graphene production rate by weighing collection vessel – target minimum 10Kg graphene from 1,000 hours of testing.
- Weekly analysis of graphene quality (Analysis carried out at Levidian HQ using Raman Spectrometer)

All critical process parameters (gas pressures, gas flows, temperatures, energy consumption etc.) will be automatically collected in the LOOP database and analysed to continuously monitor the system behaviour. Hydrogen gas samples (post vPSA step) will be periodically collected for purity analysis by external provider.

7. Project Planning

Our project will adopt the UU Innovation Project Delivery Process. At UU we understand the differences between innovation project delivery and capital programme. Due to the unpredictable nature and higher benefits risks associated with Innovation projects we have developed our innovation gate (iG) governance process which focuses on upscaling and implementation at each stage, identifies if this is not likely and therefore provides us with early indication of the need to efficiently bring a project to a close. We will use the iGs to ensure the project team inform and receive feedback from our project sponsors in UU and Levidian. This will help us align to the strategic objectives of both partner organisations as we work through the project and allow us to adjust direction if necessary.

7.1 Timelines for deliverables

We have provided a detailed programme of activities that we envisage undertaking during the delivery of LOOP phase 2 (please refer to Annex F). As Phase 2 will be a demonstration of the LOOP we have aligned our deliverables to key design, manufacturing, installation and commission project delivery requirements. In addition to this we have included deliverables for key outcomes such as carbon lifecycle analysis, of the process and potential end uses of graphene and hydrogen, social value assessment and how we plan to commercialise outcomes.

Activity	Completion Date
D1 HAZOP Report	Tue 25/07/23
D2 DSEAR Strategy	Tue 25/07/23
D3 MSP (Enabling Works) Estimate	Thu 31/08/23
D4 Enabling Works Complete	Thu 07/12/23
D5 LOOP Manufacture Complete (FAT Report)	Tue 12/12/23
D6 LOOP Commissioning Report	Tue 16/04/24
D7 Carbon LCA Report	Tue 15/10/24
D8 Social Value Assessment Report	Tue 15/10/24
D9 Commercialisation Plan	Tue 15/10/24
D10 LOOP Phase 2 Report	Thu 27/03/25
Quarterly Reports starting August 2023	28/08/23 to 17/02/25

7.2 Project management (including project team and key suppliers)

As presented in our project organogram in Annex F our project will be delivered based on a 4 level governance/quality control system with the following key roles from each organisation.

United Utilities (UU) will be the lead organisation responsible for the daily management of the project including all commercial, technical and knowledge management activities. UU will be responsible for the distribution of project funding against the completion of milestones, application of our governance process and reporting to the BEIS Monitoring Officer. UU will also support the LOOP technical development through the provision of samples, analysis, existing data and enabling works design. Following installation and commissioning UU will provide operator input.

Levidian will provide the technical knowledge of the LOOP process, making use of data from investigation in phase 1, using their Cambridgeshire testing facility, to understand the manufacturing requirements for an upscaling of the LOOP. Levidian will manufacture, install and commission the LOOP at MBC in phase 2.

Jacobs, as a subcontractor to UU, will apply their knowledge of conducting lifecycle assessments to support the development of the LOOP system and the maximisation of potential benefits through future use across multiple industries and geographies. Experts in the application of sustainability, circular economy and social value will inform the project team of how they can calculate the benefits from hydrogen and graphene production. This will be further enhanced through the development of the commercialisation roadmap showing how the LOOP can be developed such that it appeals to a broad and varied range of applications.

7.3 Risks and risk management

Risk will be managed against our risk register, throughout the delivery of phase 2, at our quarterly project Steering Group (SG) meetings (please refer to section 7.5 below).

7.4 Project Oversight, Governance and Quality Assurance

With reference to the organogram and governance diagram provided in Annex F we propose adopting a four tier governance structure for phase 2 that provides clear responsibility boundaries between each level. Requests made at work package level (Governance level 1), are reviewed and discussed, in order to make a recommendation, that meets the needs of all work packages, at steering group level (Governance level 2). These recommendations are then submitted to Project Management for approval (Governance level 3). This structure will be used for commercial and technical quality assurance and the Project Manager will confirm where additional information is required and if escalation to BEIS is necessary. This basic structure will be used by our team to address multiple requirements across project delivery including the resolution of any issues or disputes, application of changes to scope, checking and approval of design information and deliverables and consortium wide approval of quarterly reports.

To assure the quality of our deliverables we will adopt an author, checker and approver format. This will allow deliverables to be checked by the correct technical authority within the steering group organisations before being sent to the BEIS Monitoring Officer. Once checked by the appropriately qualified individuals via the steering group a recommendation will be made to the project manager regarding suitability of the deliverable for approval.

Named individuals from the project partners are provided as key steering group members. They will coordinate the input from their particular organisations and report on successes and concerns to the steering group. As the project develops there may be opportunities to add members to the steering group so that the consortium can benefit from further knowledge and understanding of a certain requirement. An example of this may be the wider adoption of the LOOP and/or its products. Advantage may be gained through input from a hydrogen specific organisation that can help us understand how best to enter their particular market and orientate ourselves for success.

7.5 Reporting Plans

Quarterly reports, having been through technical governance with our steering group, will be issued to the BEIS Monitoring Officer for review adopting the template specified by BEIS during the phase 1 project.

During delivery of phase 2 it will be necessary to conduct both work package (WP) and steering group (SG) meetings. WP meetings will be led by the work package leader (WPL – Please refer to our organogram in Annex F). These more technically focused meetings will have a standard agenda covering the following items.

- Feedback/Update from Steering Group and Project Management incl. H&S
- Current WP Programme and % complete
- Update on tasks and deliverables completed last month
- Proposed tasks and deliverables for the coming month
- Review and update of risk and opportunities register
- Review and update of Change and Issues Management Process
- Check of IP Register
- Opportunities for dissemination

Information and the outcomes of discussions from the WP meetings will be presented by the WPL at the next SG meeting along with requests relating to technical and commercial governance.

The quarterly SG meetings will be led by the Project Manager (PM). The focus of the SG meetings will be more managerial in nature with the general culture of how the SG can support the WP delivery. The following items will form the standard agenda.

- Feedback/Update from PM (including any updates from BEIS) incl. H&S
- Review of overall project programme and % completes
- Updates from each WP including summary of progress against deliverable dates and items requiring approval
- Risk Management and Mitigation plan – Any resource, documentation/deliverables and/or contingencies to be implemented
- Feedback from SG members on current quarterly report / sign off of SG of report prior to submission to BEIS
- Knowledge Management Update

All meetings will be documented, and resultant information stored on the project Microsoft Teams site. Only information stored on the “Teams” site will be reviewed during meetings as a means of assuring one version of the truth and maintain the need for stringent governance. The following table provides estimated dates for the SG meetings during phase 2.

Steering Group (SG) No.	SG Meeting Date	Project Quarterly Report Date
1	Mon 21/08/23	Mon 28/08/23
2	Mon 13/11/23	Mon 20/11/23
3	Mon 12/02/24	Mon 19/02/24
4	Mon 13/05/24	Mon 20/05/24
5	Mon 12/08/24	Mon 19/08/24
6	Mon 11/11/24	Mon 18/11/24
7	Mon 10/02/25	Mon 17/02/25

7.6 Dissemination

Dissemination will be led by the Knowledge Management (KM) Team within United Utilities. The KM team currently provide knowledge management processes, policies, protocols and systems which evaluate the benefits and impacts of organisational work programmes. The application of knowledge management processes and techniques such as action learning sets, peer assist sessions, knowledge cafes, community of practices and lessons learned adds value to Engineering work. The KM team have expertise in creating, supporting Communities of Practice to embed a community sharing culture. Having a community culture enhances people capital, as well as asset capital and ensures robust evidence underpins all decision-making. This KM team has a successful and far reaching strategy for dissemination already adopted on UU led innovation projects. This includes the facilitation of detailed dissemination planning activities, event management expertise, creation of collaborative spaces and the development of articles for publication. The Knowledge Management Team are also responsible for updating engineering asset standards in UU within which we specify what has been approved for use within our engineering designs. This presents a potential technical dissemination route within a partner organisation that is also relevant to the wider water industry. KM will be a specific agenda item on quarterly steering group meetings.

7.7 Phase 2 Project Cost Plan

Our project cost plan has been developed based on the following breakdown and sources of information.

- Engineering and Project Management Input – Based on actual cost data incurred on previous large, multi-organisation, innovation projects scaled to the requirements and duration of LOOP phase 2.
- Contractor and survey estimates – Based on figures provided within the UU cost estimating system which are developed from previous actual incurred costs for similar schemes.
- UU Instrumentation and laboratory analysis – Provided by the UU departments
- Levidian funding requirements – Estimate based on a detailed breakdown of the LOOP constituent parts and requirements for the innovation development for phase 2 (detailed breakdown provided in Annex F).

If we are able to go ahead with phase 2 we will adopt the standard UU procurement rules. This will include contracting with existing deliver partners where onsite works and equipment are required and therefore using tried and trusted procurement frameworks. Where an existing framework agreement is not in place, we will look to gain competitive prices where possible. Unfortunately, due to the nature of innovation projects, this is not always possible as the equipment to be purchased is new, or a recent invention, and does not therefore lend itself to multi-supplier procurement competitions.

By adopting this approach, we are providing increased certainty regarding outturn costs and employing procurement professional as a means of achieving value for money.

The following table provides an estimated breakdown of the potential phase 2 costs.

Cost Element	Estimated Total Cost	Percentage of Project Total
Labour	£742,434	24.4%
Materials and Equipment / Works	£1,985,850	65.3%
Subcontracts	£175,950	5.8%

Travel & Subsistence	£8,900	0.3%
Overhead	£128,615	4.2%
Project Total Estimated Cost	**£3,041,749**	

7.8 Assumptions log

Assumption	Description	Mitigation
Biogas Quality	Biogas from primary digestion of sewage sludge tend to be in the region of 60 to 65% methane. This can vary slightly depending on the wastewater treated and therefore the contents of the sludge removed in the treatment process.	In phase 1 we have completed sampling and analysis of the biogas produced at MBC, however, this may still vary during the operation of a demonstration scale LOOP.
IT Security	LOOP will require access to signals from the UU MBC plant so that it knows when to shutdown safely. As the LOOP team will access control of their system remotely we need to confirm that no IT risk exists for business as usual operating systems at MBC.	UU have engaged the IT Security Team to review the gaps and potential mitigations that would remove this risk.

8. Commercialisation Plan

In this project, LOOP is being applied to the water sector, utilising biogas generated by anaerobic digestion of sludge to produce high-value hydrogen and graphene outputs. It also has the potential to utilise biogas from future (e.g., mainstream cold digestion) anaerobic wastewater treatment. How the LOOP technology is applied in the water sector operations is predicated by renewable energy, the availability of biogas, and the value it can generate across the wastewater and Bioresources processes.

8.1 Target market for LOOP generated hydrogen

Low carbon hydrogen will be critical for meeting the UK's legally binding commitment to achieve net zero by 2050, and Carbon Budget Six (78% emissions reduction) in the mid-2030s (HM Government, 2021). In terms of value, at the release of the UK Hydrogen Strategy in 2021, UK Government indicated a value in the UK of £900 million of investment, potentially rising to £13 billion by 2050. It is also to be noted that the Energy Security Strategy (2022) raised the ambition of hydrogen capacity in the UK by 5GW to 10GW by 2030, therefore the investment to 2030 would now be significantly higher.

The opportunities for on and off-site uses of hydrogen will be dependent on a number of factors including technical, financial and location. Key on-site uses include use in heavy good vehicles, direct and indirect industrial heating and to increase biogas yield. Off-site uses include grid injection and supply to local refuelling stations.

For the onsite opportunities, it appears to be largely a commercial decision for the utility company to determine whether it is economical to invest in replacing and retrofitting existing assets to make use of the generated hydrogen. The offsite opportunities are largely reliant on other markets (hydrogen grids and large-scale hydrogen refuelling stations) reaching a suitable scale and level of maturity.

8.2 Target market for LOOP generated graphene

Graphene is a one-atom thick sheet of carbon atoms arranged in a honeycomb-like pattern. Graphene is considered to be the world's thinnest, strongest and most electrically and thermally conductive material. Graphene as a commercial product is typically referenced in two broad material forms: a bulk material (either as a powder, solution of paste) or a continuous thin film. These products are produced by a range of top-down and bottom-up processes.

Some key properties of graphene are as follows; high electrical conductivity, high strength, high surface/weight ratio, high light transparency, high flexibility, high sensitivity for chemical detection, high thermal conductivity and a high barrier material (impermeable if defect-free). These properties make graphene suitable for multiple applications across electronics, materials, optics, chemical and biosensors, heat and energy storage, and energy generation.

Despite predictions of huge growth over the next decade, current markets for graphene-enhanced products appear nascent in their maturity. Products are either still being developed in experimental or trial settings, or where commercial products do exist, they are typically priced far higher than more established alternatives. We expect this commercial picture will change dramatically as graphene production scales, and graphene-enhanced manufacturing processes become more commercialised.

We have established that, under the default arrangement, LOOP produced graphene would be owned by Levidian, who would then target supply towards the following markets: construction, energy storage, coatings, and polymer composites. Levidian intend to pay a recovery cost to the water utility for every kilogram of graphene produced. Initial indications suggest that this recovery cost would be in the £10-£12 per kg range. Informal conversations with UU suggest that this level of recovery cost compares favourably to alternative revenue generation avenues they could pursue for their biomethane, such as selling it to national grid distribution network, making LOOP an attractive commercial choice.

8.3 LOOP deployment model

There are currently two models through which LOOP can be deployed within a water company:

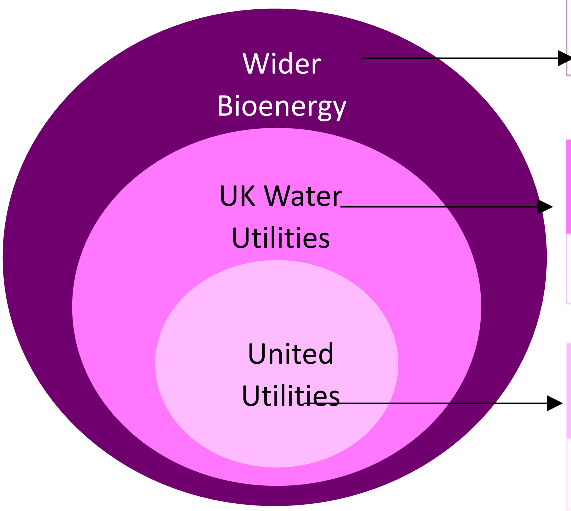
- **Lease Model**: LOOP would be deployed over an indicative 10-year period.
- **Capital Purchase Model**: The water company would own the asset, and Levidian would operate it on their behalf.

The options for ownership position around valuable outputs are as follows:

- **Hydrogen**: Levidian's base offer is that all input and output gases used and generated by LOOP remain owned by the water company. Therefore, hydrogen outputs can be owned by the water company.
- **Graphene**: There are several arrangements available for ownership of the graphene output including: Levidian taking ownership and paying the water company a "recovery cost" of £10-12 per Kg (default), negotiating a split of the yield if the water company has a predictable need for the graphene, or allowing the water company to buy back graphene from Levidian as and when it needs it.

8.4 Quantification of the Target Market for LOOP Technology

To understand the size of the commercial opportunity for the LOOP technology in the UK Bioresource sector, we have conducted a bottom-up analysis of the quantity of biogas produced by UU and then by the wider UK Water Sector. We have then applied a series of calculations to understand the quantities of methane, hydrogen, and graphene that could be produced from this biogas. Together these analyses give a view of the total potential market size for LOOP in UU and the wider UK Water Sector.



Further UK biogas markets - unquantified	
• Agricultural residues • Animal manure • Biowaste • Industrial wastewaters	• Permanent grassland • Roadside verge grass • Sewage sludge

Scenario	Methane (t/y)	Hydrogen (t/y)	Graphene (t/y)	Example # of LOOP 1000 units
Theoretical Maximum	363,528	72,705	98,152	489

Scenario	Methane (t/y)	Hydrogen (t/y)	Graphene (t/y)	Example # of LOOP 1000 units
150m3/hr to LOOP	487	97	131	1
2000m3/hr to LOOP	6495	1299	1753	9
Theoretical Maximum	**34970**	**6994**	**9442**	**47**

Figure 8.1. Summary comparison of the production values for each target market

Using the LOOP system, over 95% of the biogenic carbon in biogas is transformed into products that are not classed as direct greenhouse gases (hydrogen, carbon monoxide, acetylene, and graphene). Figure 8.1 above shows that there is a significant target market for the LOOP technology, both within UU and the wider water sector. However, a number of avenues need to be explored before a robust and defensible addressable market size can be determined. Recommended next steps include:

- Reflect Outcomes from the Lifecycle Carbon Assessment in the Commercialisation Plan to provide a multi-dimensional view of the commercial potential of LOOP.
- Conduct an Economic and Financial Analysis of the 'System Impact' of LOOP considering its integration into a wider system. For example, LOOP may "take away" valuable resources such as biomethane from other parts of the system. Suitable replacements would need to be found and potentially purchased if UU reduced its volume of biomethane to grid.
- Bottom-Up Sizing of the Wider UK Bioresource Sector Opportunity to give an indication of the total market size for LOOP in the UK.

More details regarding commercialisation can be found in Annex G.

Analysis of gaps in data

This Phase 1 feasibility project has provided an excellent opportunity to evaluate the key scientific and engineering requirements for generating hydrogen from biogas. Our confidence in the proposed LOOP demonstrator system has increased, but there are still several gaps in data that may impact the viability of our H2BECCS solution.

- Lower than anticipated graphene yields from feasibility studies – improved yields will make the LOOP process more economically attractive.
- Carbon monoxide is a new product generated from LOOP when biogas is used as feedstock. An evaluation of the potential value of carbon monoxide needs to be carried out.
- The long-term stability of the process still needs to be established – laboratory feasibility experiments lasted 6 hours but we are aiming for 24/7 operation of the demonstrator unit.