Hydrogen BECCS
(Bioenergy with Carbon Capture and Storage) project
Funded by BEIS

Hydrogen from waste via dark fermentation

Final report

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Alps Ecoscience Ltd

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3 Abbreviations

AD	Anaerobic digestion
CO_2	Carbon dioxide
COD	Chemical oxygen demand
DF	Dark fermentation
H_2	Hydrogen
HRT	Hydraulic retention time
KPI	Key performance indicator
OFMSW	Organic Fraction of municipal solid waste
MSW	Municipal solid waste
NI	Northern Ireland
PLC	Programmable logic controller
VS	Volatile solids

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4 Executive summary

This project tested the process of dark fermentation (DF) at pilot scale using a feedstock of Organic Fraction of Municipal Solid Waste (OFMSW), extracted via a specialised wash plant for black bin waste. The feedstock was processed using Alps' innovative pre-treatment process and then fermented under a variety of pH, temperature, feed rate and microbial conditions. The DF process successfully produced hydrogen from 6% solids, at a concentration of 45% by volume in the off gas, at an average rate of 4.8L/day of hydrogen, with a peak rate of 11.5L/day of hydrogen. Large-scale plants typically operate at 12% solids which would double hydrogen output at the same yield rate. The yield rate could be further improved with feedstock co-digestion, pre-treatment, and process optimisation. We would expect a further doubling of output, bringing yield closer to the theoretical expected output. However, for prudence all calculations presented here assume the lowest level of hydrogen output from the study.

Dark fermentation was found to be a rapid process that required a low pH and a fast feed rate. The study showed that the process was enhanced by the addition of specific bacteria, and these were successfully cultured in a laboratory in sufficient quantity for this pilot scale test. The feedstock, OFMSW, was found to enhance the DF process as it contained a diverse community of bacteria as well as having excellent energy potential. This suggests that OFMSW is a viable and readily available feedstock for green hydrogen production.

The DF process targets the carbohydrate portion of the feedstock, accessing the sugars and converting them to hydrogen and carbon dioxide. The residual feedstock is converted to organic acids which when digested via anaerobic digestion (AD) produces methane, in an established industrial process. The DF step converted 16.8% of available feedstock, which is roughly equivalent to the carbohydrate content of the feedstock. The output from the DF process is a highly suitable feedstock for AD, producing methane which would provide power and heat for the DF step and additional revenue from biogas production. The hydrogen would therefore be incremental with neutral production costs and carbon dioxide (CO_2) emissions beyond the existing biogas production process.

As a result of phase 1, we now understand the following.

- We have identified and isolated the biological conditions and bacterial species required to ferment hydrogen.
- These species target the sugars and carbohydrates within the feedstock.
- The DF step requires a rapid processing time which would enable a reduction in AD processing time by 30%, from a typical 30 days to 20 days, reducing plant size and CAPEX or increasing biogas output from existing assets.
- A continually fed stable solution was achieved but there is still significant scope to increase solids loading and optimize conversion.
- Dark Fermentation works in conjunction with AD as a synergistic process.
- There is process inefficiency at pilot scale which may have reduced the feedstock conversion.
- OFMSW is a suitable feedstock for DF, although optimal feed rate and carbohydrate % destruction is still to be achieved

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Next steps

- Improve process efficiency with scale, through higher solids loading and feed rates due to larger tanks, pipes and pumps.
- Improve conversion efficiency and system output by further experimental run time and process changes.
- Increase hydrogen yield through co-fermenting with high-glucose feedstocks to achieve better conversion of carbohydrates and higher hydrogen output.
- Automate control systems to fine tune processing (pH correction, loading rate, partial pressure)
- Apply additional pretreatment to the feedstock to increase the surface area available for conversion.
- To continue to test if a theoretical yield of 107ml per gram of VS (up to 20x the phase 1 result) can be achieved at production scale.

The commercial case is inconclusive for this type of hydrogen production at the end of phase 1. The economic model for small scale hydrogen production is difficult to define as there is no pre-existing hydrogen economy or infrastructure. However, the base assumption of developing upgrade technology for the biogas market to support decentralized hydrogen production from waste streams remains valid. We are therefore pursuing the development of a phase 2 demonstrator to refine the technology and determine the maximum volume of hydrogen available from this process design.

5 Background

The aim of achieving a 'zero carbon' future depends heavily on the development of low- and no-carbon energy solutions and the replacement of oil, gas and coal use in favour of non-fossil fuels. Hydrogen has great potential as a fuel in a zero-carbon future as it does not emit carbon dioxide as it burns, is storable and has a high energy density (3 times that of petrol). Hydrogen has a wide variety of uses, such as petroleum refining, steel production, methanol and ammonia production, and transport.

In the future, the amount and proportion of hydrogen used for transport is expected to grow considerably, and growth is also expected in heating and power generation applications. Hydrogen is currently made mostly by electrolysis, but this requires large amounts of electricity. As the demand for hydrogen increases, alternative sources of hydrogen will be required.

27 million tonnes of black bin waste are produced in the UK (https://www.gov.uk/government/statistics/uk-waste-data/uk-statistics-on-waste), with approximately 50% of this mass being organic matter. Current solutions for disposal of this organic matter include incineration and landfill. This waste is problematic to process as it requires separation and can be highly variable. The separated organic matter in the black bin waste is commonly referred to as OFMSW (Organic Fraction of Municipal Solid Waste).

The Alps Eco Dark Fermentation project aims to make use of OFMSW to make hydrogen through a process called Dark Fermentation. This is a sub-process of anaerobic digestion, which normally converts organic matter into methane. By modifying the conditions of the process, hydrogen and carbon dioxide are produced instead of methane (figure 2).

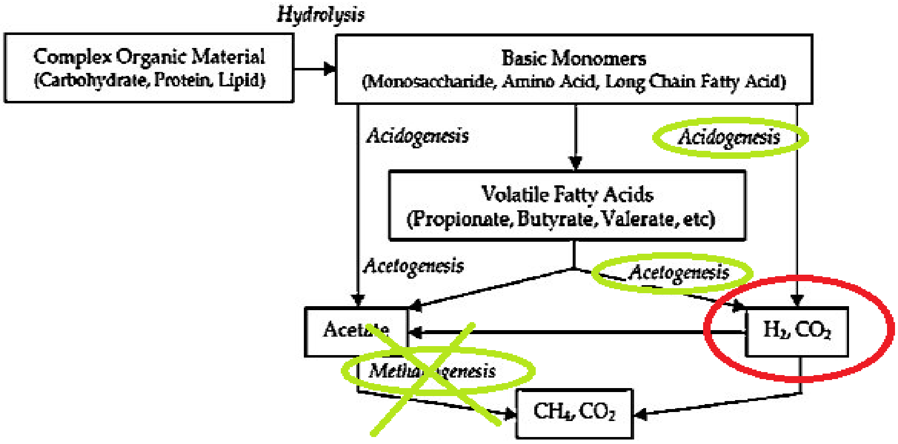

Figure 1: The process of anaerobic digestion with process adjustments to favour dark fermentation.

This project has the potential to vastly improve the economics and the carbon footprint of current waste disposal processes, as well as providing a new, low-energy process for the generation of hydrogen.

6 Life cycle analysis

We have performed a life cycle analysis (LCA) of the phase 1 experimental work which shows the inputs and emissions of the process. A full listing of the information used is provided in the appendices.

Resources	Water	15591	kg/kgH_2
	OFMSW	5239	kg/kgH_2
	Electricity from mixing	624	kWh/kgH_2
	Electricity for plant use	1497	kWh/kgH_2
	Heat	1454	kWth/kgH_2
Emissions	CO_2 emissions from acid use	15.41	kg/kgH_2 [1]
	CO_2 emissions from lime use	80.61	kg/kgH_2 [2]
	CO_2 emissions from electricity	758.94	kg/kgH_2 [3]
	Total CO_2 emissions	854.96	kg/kgH_2

[1] 0.14 kgCO_2/kg (https://legacy.winnipeg.ca/finance/findata/matmgt/documents/2012/682-2012/682-2012_Appendix_H-WSTP_South_End_Plant_Process_Selection_Report/Appendix%207.pdf)
[2] 0.94 kgCO_2/kg (https://www.sciencedirect.com/science/article/abs/pii/S0959652622028116)
[3] 0.21233 kgCO/kWh (https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021)

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Table 1: Life cycle analysis of the phase 1 experimental production of hydrogen.

These figures were calculated from the actual resource use and hydrogen production during phase 1. In a large-scale operation there would be significant opportunities to reduce the footprint in all areas. For example, water use would be reduced by recycling process water, a frequent practice in anaerobic digestion processes. The electricity use due to onsite electricity demand and mixing would in relative terms be far smaller in a full-scale system. The heat requirement would be equivalent at any scale; however, a large-scale hydrogen production process would be coupled with an anaerobic digestion process. Therefore, the process would be heated by carbon neutral heat from the biogas CHP and would provide a high-temperature output stream which would reduce or remove heating requirements in the anaerobic digestion process downstream, saving heating emissions.

The carbon mitigation opportunities of the process are:

- Avoidance of uncontrolled breakdown of OFMSW in landfill – a saving of 587.3 kgCO_2/tonne OFMSW[4]
- Avoidance of municipal solid waste (MSW) incineration – saving 21.3 kgCO_2/tonne MSW
- Increasing biomethane yield in anaerobic digestion plants by re-injection of hydrogen – increased yield by 10% (estimated), therefore increasing carbon-neutral electrical and heat output by 10%.

6.1 Biomass feedstock

The feedstock, OFMSW, is produced from black bin waste via a wash plant. OFMSW is a feedstock for anaerobic digestion that will be diverted to dark fermentation, therefore it is a question of the project scope as to whether the energy required to produce the feedstock should be included in the LCA. This represents an area of uncertainty within this study.

6.2 Land use

The feedstock used in this process is a waste rather than a primary resource, therefore has no land use requirement for its production and therefore has no emissions associated with direct or indirect land use changes. Use of this feedstock for dark fermentation will reduce the solids going to landfill and in time may be a first stage in the development of landfill mining which will lead to carbon-negative land use emissions.

6.3 Levelised cost of Hydrogen (LCOH)

This innovation seeks to create hydrogen by making improvements to the current AD process that produces biogas. Leveraging existing infrastructure to make an economically viable manufacturing process for incremental hydrogen whilst maintaining the same yield of biogas. Phase 1 testing shows that hydrogen can be fermented with no additional process energy input or loss of biogas yield. What remains unknown is the maximum

[4] Reference: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021

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amount of hydrogen volume available, the point at which biogas production is reduced and the economics of the combined process. Based on conversion efficiency Dark Fermentation achieved in phase 1, the LCOH has been calculated as follows using the LCOH workbook supplied by BEIS:

Cost Elements	Baseline (£/MWh HHV H2)	With applicant's technology (£/MWh HHV H2)	Change (%)	Description
Capex £/MWh	31.2	427.7	1271%	Levelised capital cost
Fixed Opex £/MWh	51.5	6355.1	12233%	Levelised fixed operating costs e.g. rent, salaries
Variable Opex £/MWh	0.0	652.7	N/A	Levelised variable operating costs eg feedstock, energy consumption
CO2 T&S cost £/MWh	10.1	13.2	31%	Levelised cost associated with the transport and storage of the captured CO2*
Carbon cost emitted (fuel) £/MWh	37.6	37.6	0%	Levelised carbon cost for CO2 emitted to atmosphere.*
Total £/MWh (excl. carbon cost)	130.4	7486.3	5642%	Levelised cost of hydrogen without cost of sequestered carbon.
Carbon cost sequestered (fuel) £/MWh	-42.6	-42.6	0%	Levelised carbon cost for CO2 sequestered*
Total £/MWh (incl. carbon cost)	87.8	7443.7	8376%	Levelised cost of hydrogen with cost of sequestered carbon.

Table 2: Levelised cost of hydrogen from BEIS workbook.

The residual CO_2 is available for CC&S using established technologies. No reduction over current costs is assumed.

The dark fermentation of OFMSW carried out by Alps during the phase 1 BECCS produced 1.9ml of H_2/g volatile solids consumed. The treated feedstock made the second stage Anaerobic digestion process 30% more efficient by reducing the hydraulic retention time from a typical 30 days to 20 days. The process also accessed more feedstocks normally left undigested in the anaerobic process thus maintaining the biogas production rate approximately as before. The solution that Alps is developing is easily deployable to existing AD plants thus increasing the potential biomethane output by 50% without incurring any significant capital investment.

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Alps commercial Dark Fermentation solution will cost around redacted to deploy to a typical AD plant with no incremental OPEX costs as the heat and energy used in the process is offset by savings in the AD part of the process. Operation of the DF plant can be undertaken by existing plant personnel. There is an increase in chemical consumption but digestate recycling mitigates partially against this. With improvements in the fermentation process hydrogen production could increase 20-fold, reducing the current LCOH.

7 Demonstration project

7.1 Functional test

The functional test experimental setup consisted of three fermentation tanks of 50L working volume, each with a built-in mixing and temperature-controlled heating system.

Figure 2: The dark fermentation functional test set-up.

The feedstock was mixed, cavitated, treated with a catalyst, inoculated with digestate from an existing anaerobic digester, and acidified in an open tank before transfer to the Dark Fermentation tanks. The tanks were sealed and individual Tedlar bags were attached to each tank for gas collection. The tanks were heated and left, mixing continuously, to ferment. During the fermentation, analysis of the gas was performed at varying intervals.

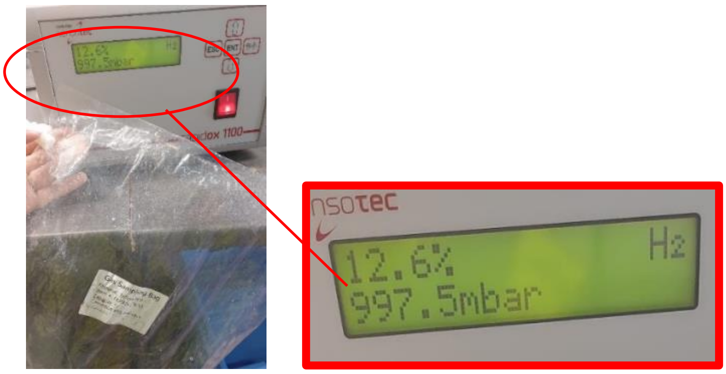

Figure 3:Gas analysis during the functional test.

Samples of the mixing tank and fermenters were taken before and after the fermentation and laboratory tests were performed to show the effect of the fermentation on the chemical and biological content of the feedstock.

7.1.1 Hydrogen production – run 2

Run 2 was the first experiment to produce gas. We found that although a lot of gas was produced, hydrogen was only produced in tank 3. After the first two hours, tanks 1 and 2 produced hardly any gas, whereas tank 3 produced a small amount. The concentration of hydrogen in tank 3 was measured at 10.3%. Full results from run 2 are presented in the appendices.

7.1.2 Hydrogen production – run 3

The hydrogen production in run 3 was more consistent but we also found that the tanks also produced unwanted gases, i.e. methane, and less carbon dioxide. The total amount of gas produced was higher in all three digesters. The largest amount of hydrogen was produced by tank 2.

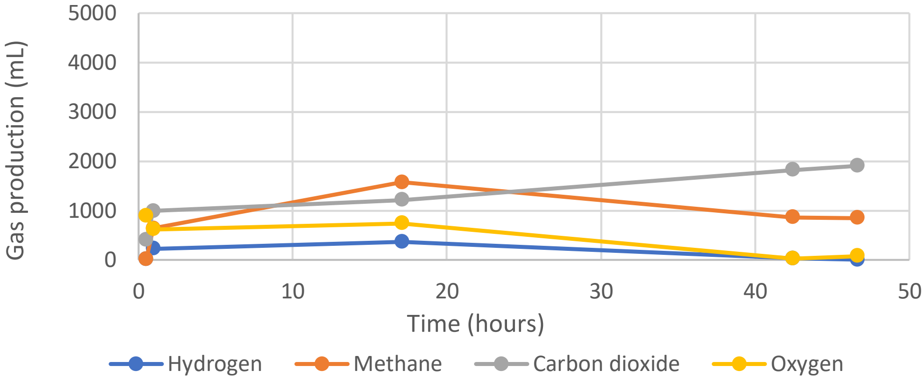

Figure 4: Hydrogen production in run 3 Fermenter 1

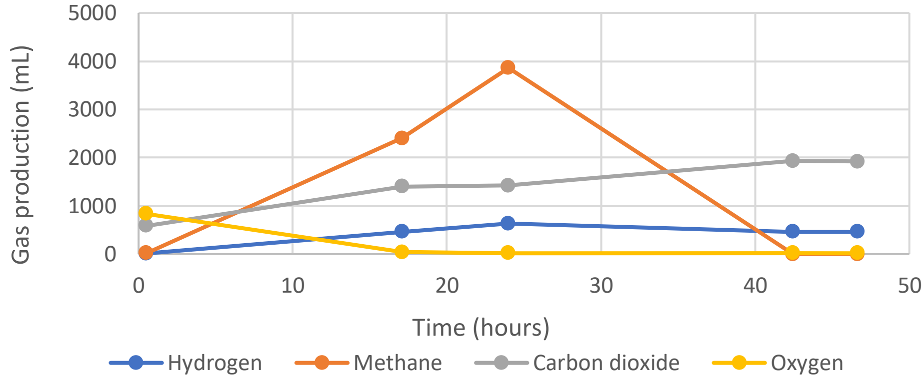

Figure 5: Hydrogen production in run 3 Fermenter 2.

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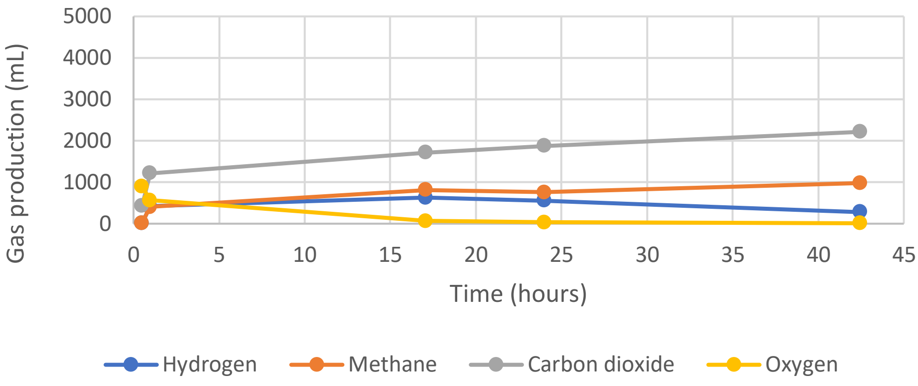

Figure 6: Hydrogen production in run 3 Fermenter 3.

7.1.3 Functional test - discussion

In run 2, we noted that due to the non-uniform consistency of the feedstock, a lot more fibre was added to tank 3 compared to tanks 1 and 2, and it is feasible that this would explain the difference in hydrogen production.

In Run 3, we found that the digesters produced significantly more methane compared to Run 2 due to the lack of pH adjustment.

We improved the experimental procedure during the functional test, which was a useful learning experience to understand the subtleties of the process. Overall, the functional test satisfied us that we had the capability of making hydrogen through the process of dark fermentation.

7.1.4 Conclusions

Three runs of the functional test were performed in triplicate. The tests showed that the acidic environment and microbial population were key to successful hydrogen production.

7.2 Performance test

The performance used the same fermentation tanks as the functional test, running in a continuous process.

7.2.1 Culture preparation

Liquid samples from the OFMSW feedstock and inoculums from two test anaerobic digestion sites were scored on agar plates and incubated to select for hydrogen-producing bacteria. Several colonies were picked and grown in a nutrient rich media. This produced a culture of hydrogen-producing bacteria.

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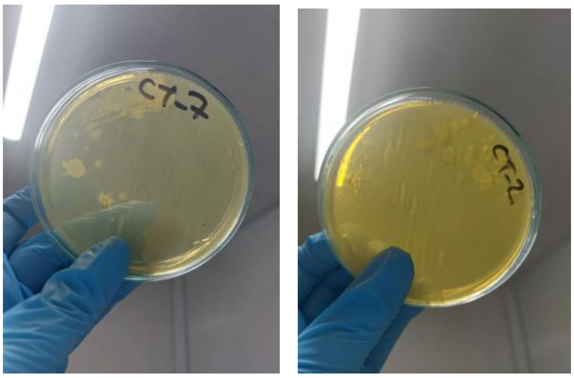

Figure 7: Agar plates showing growths of hydrogen-producing bacteria.

7.2.2 Test commissioning

The feedstock was mixed and pre-treated in a 180L open tank before transfer to a 250L feed tank where it was diluted to approximately redacted – commercially sensitive matter and acidified. The prepared feed was then used to fill the dark fermentation (DF) tank and then a mixed culture of hydrogen-producing bacteria, described previously, was added. The tank was then purged with nitrogen and sealed, then heated. The feed system was set up to pump feedstock to the dark fermentation tank.

Figure 8: The dark fermentation process in 'continuous' setup mode.

More feedstock was treated and added to the feed tank every 2-3 days.

7.2.3 Results and discussion

The hydrogen production in the performance test was very variable because of the mechanical problems encountered during the first four weeks, which caused overheating, underheating, breaks in feeding and air ingress at various points.

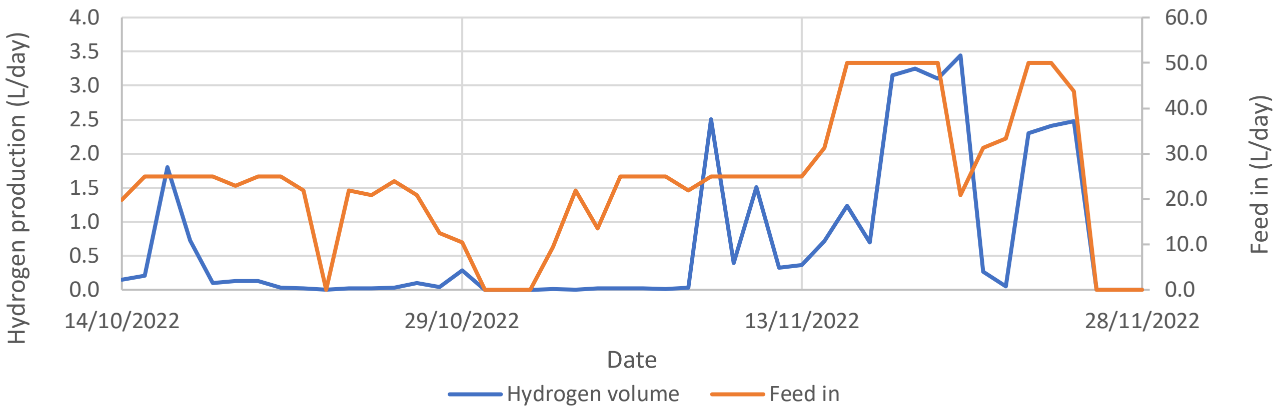

Figure 9: Hydrogen production during the test period - comparison of production rate vs feed rate.

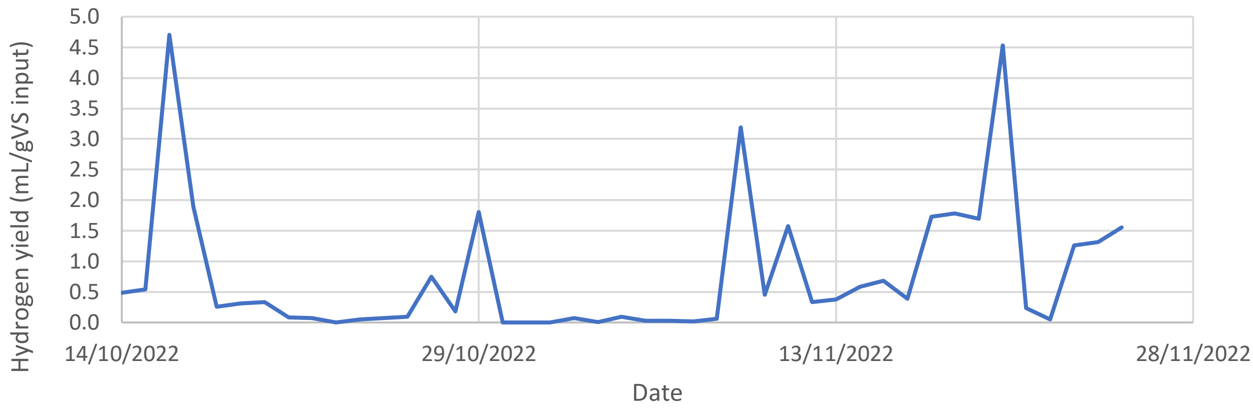

Figure 10: Hydrogen production during the test period - yield per g of volatile solids (VS).

Just after the fermenter was inoculated (14th October, 24th October, 8th November), there was an increase in both hydrogen production volume (L/day) and hydrogen yield rate (mL/gVS (volatile solids) input, the blue trend lines in Figure 10b). After the inoculations on 14th and 24th October, mechanical issues caused the process to cool down and allow oxygen ingress, which inhibited the bacteria metabolism and stopped the fermentation from working. After the mechanical problems were resolved, the third re-inoculation (8th November) was successful and the hydrogen production was maintained over a sustained period. The feed rate (shown by the orange line in Figure 10a) was increased on 14.11.22 and resulted in higher and more sustained hydrogen yields. This indicates that the bacteria in the process were more suited to a faster feed rate and a shorter hydraulic retention time.

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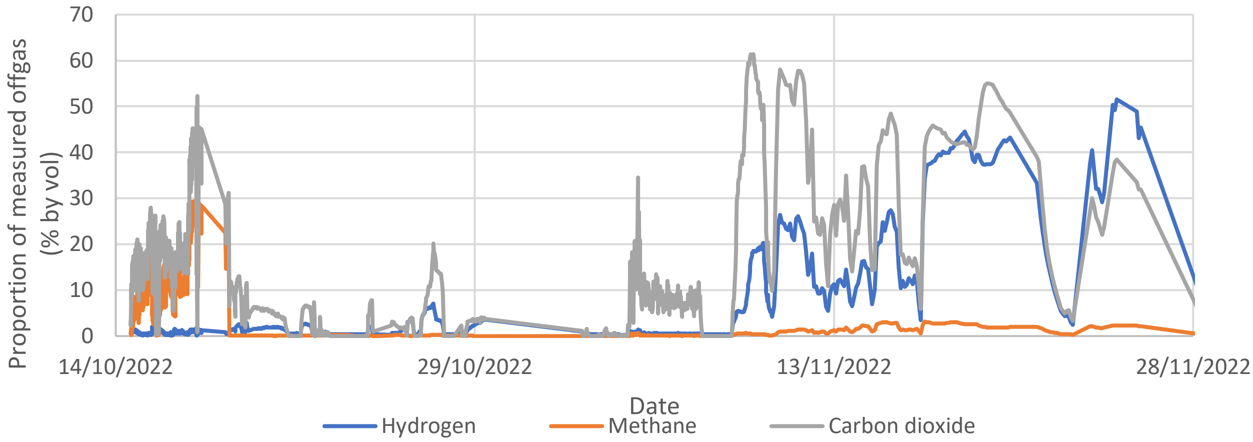

Figure 11: Hydrogen % in off gas during the test period.

The gas analysis in Figure 11 shows the hydrogen % in the off gas compared to the three other gases that were measured, methane, carbon dioxide and oxygen. The graph shows a large proportion of methane and carbon dioxide present after the first inoculation (14.10.22), meaning that the methanogenic bacteria had not been inhibited during the setup. The second inoculation (24.10.22) produced a small rise in hydrogen production, which then reduced to zero. The third, successful, inoculation on 8.11.22 produced an immediate rise in the proportion of hydrogen and carbon dioxide in the off gas. During this final period the gas proportions stabilised to show what might be expect in a stable, continuously-running system – 45% hydrogen, 50-55% carbon dioxide and 0-5% methane.

The Chemical Oxygen Demand (COD) in a liquid is a direct predictor of the biomethane potential of a feedstock, as 1 kg COD produces 350L of methane if the conversion is 100% efficient. The average COD before and after fermentation was 49,246 and 40,984 mg/L respectively, a reduction of 16.8%. The dark fermentation process therefore reduced the potential biogas production of the feedstock by 16.8%. However, this is counteracted by the fact that the COD is more solubilised during the process and the efficiency of the anaerobic digestion process (that it, the % conversion of the organic content of the feedstock) will be increased. A normal anaerobic digestion process with a similar feedstock is about 85% efficient, and it would be reasonable to expect an increase of 5-10% efficiency with this feedstock improvement. Therefore, it is reasonable to assume that the methane production volume via anaerobic digestion from this feedstock would not be affected by this extra step.

Samples of the cultures grown from the feedstock and inoculums were sent for identification at a certified microbiology lab. The species identified were largely from the genuses Enterobacteriaceae and Clostridia, which are the main genuses of hydrogen-producing bacteria.

7.2.4 Conclusions

Following the resolution of the mechanical problems, the dark fermentation continuous process was very successful, producing a gas with hydrogen content of 40-45% and carbon dioxide of 50-55%. The process was very sensitive to oxygen ingress and was most successful at a faster feed rate, with a shorter hydraulic retention time. A key aspect of the successful dark fermentation process was the introduction of a microbial population that had been specifically selected for the conditions of dark fermentation.

Next steps in the experimental process would be to continue reducing the hydraulic retention time to find the optimum feed rate, and to investigate the effect of adding glucose to boost microbial growth.

7.3 Key learnings

This section summarises the key learnings. Further details are provided in the appendices.

7.3.1 Operational learnings

The collection of reliable data was a key learning point. The frequency of testing and the need to react to the lab results means onsite testing is preferable for most operational tests. This will require a more highly trained staff and a wider range of lab equipment and consumables in a subsequent phase. The collection of data was split across several sources (external and internal labs, different pieces of measurement equipment). For more reliable data collection, these systems would benefit from consolidation into a single reporting system and a single point of contact. Readings should be automated where possible (for example, by linking the equipment into a control panel or PLC) to ensure that data is still collected when the principal operator is off site. A fully digital recording system will be preferred for future projects, to reduce re-keying and make data immediately available on and off site.

The acid environment was very corrosive to the immersion heating elements and probes, resulting in failures. Once the heating was replaced with externally mounted trace heating the problem was alleviated.

System shutdown was often caused by pump and pipe blockages. This issue was removed by increasing the pipe gauge and pump size throughout the system, adding non-return valves where appropriate, and swapping the pump-mixing system for a mechanical tank mixer. Oxygen ingress and poor gas production were a problem at the start of the project and these issues were also solved by the pipework and pump changes.

7.3.2 Project management learnings

Despite significant planning, Alps underestimated the amount of project management and facilitation required in the first 3 months of the project. New recruits changed the dynamics of teams and extra facilitation was required to achieve optimal performance. There was an experimental learning premium borne by the project and some activities took longer than anticipated because they had never been done before. There were also additional project meetings and brainstorming sessions required in problem solving and then communicating next steps within the team. The introduction of daily 15-minute scrums after 4 weeks proved beneficial in problem solving and managing risks. It also ensured momentum and focus on deliverables. Actions minutes after every meeting was beneficial in tracking next steps and establishing accountability. It also proved a simple audit trail for the project manager.

Purchasing was the most challenging aspect of the project. First choice equipment and parts were in short supply and prices inflated as a result. During the 4-month period from the application to the project's start, lead times doubled or tripled. Equipment containing sensors or microchips went from 4 weeks to 16 weeks delivery. For a six-month project this was immensely challenging. This was overcome with the use of substitutes or used equipment. This did result in higher ongoing maintenance and increased fabrication time, but the research equipment was built to specification and performed its function. Supply chain issues persist but can be mitigated by the ordering of additional spare parts which will inflate future budgets or by extending project timelines.

The unique economic environment through spring and summer 2022 resulted in lots of changes in the availability of the project sub-contractors. During the festival season electricians and plumbers were being offered double rates so were simply unavailable. For projects of less than £5,000 many were unwilling to complete the BEIS forms required for subcontractor approval. The learning going forward on short deadline projects is perhaps to build a roster of 3 sub-contractors per trade and complete the BEIS forms in advance, so switching is simpler. For phase 2, an electrical engineer will be included on the project team, as it is the most used trade.

8 Phase 2 engineering design

8.1 Overview

For Phase 2, Alps will submit a proposal for a commercial demonstration plant.

- Redacted – commercially sensitive.

Site plan

- Redacted – commercially sensitive.

8.2 Description of plant and technology

The proposed demonstrator facility is a combined Dark Fermenter and Anaerobic Digester facility.

- Redacted – commercially sensitive

8.3 Benefits of this model

- A circular economy demonstrator site. The location can be a regional centre of excellence for waste to energy innovation with potential to attract investment.
- Demonstrates an integrated solution with full lifecycle waste management (doorstep to digestate) for black bins.
- Redacted – commercially sensitive

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9 Phase 2 project plan

9.1 Timelines for deliverables

- Redacted – commercially sensitive

9.2 Project management (including project team and key suppliers)

- Redacted – commercially sensitive

9.3 Project costs and funding

- Redacted – commercially sensitive

9.4 Risks and risk management

The project will maintain a risk register, tracking all changes in risk using a RAG status report. A report will be published every month. Changes will be discussed internally with the Project Director and with the PMO and BEIS on quarterly basis or sooner for major risks. The site will be compliant with all operating legislation.

9.5 Quality assurance

All construction and equipment will be subject to contract and warranties. The project will include a life cycle analysis conducted by an environmental consultancy as well as a high-level process audit. Key lab samples will be parallel tested at 3rd party facility to provide a benchmark and independent verification. The project will maintain separate accounts which will be audited annually. The plant will be audited prior to commissioning. A health and safety officer will be appointed.

9.6 Project oversight and governance

Project Director is responsible for the budget and deliverables. Clear roles and responsibilities with a defined escalation process to the Project Director and the Steering committee. The project manager will operate to agreed project plan, managing change and risk registers.

9.7 Reporting plans

The project Director will provide a monthly written report to the PMO and will conduct a video meeting. On a quarterly basis, there will be a face-to-face meeting with an extended presentation to the PMO and BEIS. This will be at the demo site and include a site tour.

9.8 Disseminating the demonstration results and key learnings

Alps will replicate the model used in phase 1, which delivered success. This includes press release, website, and social media posts, presentations to industry events and outreach to potential clients.

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10 Commercialisation

10.1 Target Market

Alps' focus is on green hydrogen as an upgrade technology for the Anaerobic Digestion sector, specifically biogas, waste management and water treatment industries. Within this market there are currently 750+ anaerobic digestion facilities of varying scales in the UK. Hydrogen production is incremental to this existing process because:

- Operating licences are already in place
- There is no additional heat or power for the DF step
- Return on capital is high
- The carbon impact is lower compared to new builds

This approach provides greater speed to market than new builds and Alps believe there is demand of hydrogen upgrading.

10.2 Market sizing

We will target biogas plants with over 150 tonnes daily feeding, approximately 300 sites (45% of the existing UK market). By 2035 this can deliver a nationally distributed supply chain of hydrogen from dark fermentation.

10.3 Deployment plan

The commercial deployment plan is as follows;

- Redacted – commercially sensitive

10.4 H2 BECCS contribution

Alps' DF+AD solution offers a unique economy of production and GHG (greenhouse gas) reduction for hydrogen generation. One which enables rapid market expansion of the biogas sector into hydrogen. Requiring lower capital investment and leveraging established framework for compliance, safety, planning and commercialisation. Alps' technology extends the menu of available feedstocks, offsetting the environmental impact of existing waste treatment methods whilst turning a waste into a valuable and secure energy resource with integral CC&S via existing technologies. Both are aligned with the UK governments NET ZERO commitments.

This project targets waste streams which currently release biogenic CO_2 and produce further CO_2 emissions in disposal, seeking instead to produce a green fuel with reduced CO_2 emissions across the lifecycle. The OFMSW used in the DF research offers the opportunity to utilise all the 6.6 million tonnes of biodegradable municipal waste currently sent to landfill annually in the UK. In 2019 the total volume, 13.7 million tonnes of landfill accounted for approximately 14 mega tonnes of CO_2. If DF+AD could utilise the organic fraction biogenic CO_2 is reduced by 6.7 mega tonnes per annum.

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11 Appendix 1: Life cycle analysis full table

The following table shows the calculations and figures for the Life Cycle Analysis.

Table redacted – commercially sensitive

12 Appendix 2: Dark fermentation demonstration project

12.1 Assumptions

For the experimental design, the following assumptions were made:

- The feedstock would be OFMSW at a total solids value of 0-25% and a volatile solids value of approximately 0 to 25%
- The volatile solids would make up approximately 30% to 70% of the feedstock total solids
- The level of solids destruction via dark fermentation would be 0% -50% of the volatile solids
- The dark fermentation would require an acidic environment
- The dark fermentation would be conducted in an oxygen-free atmosphere, at a temperature above ambient.
- The dark fermentation would require a specialised set of Microbia (identity unknown at the start of the project) that could be grown from anaerobic digestion inoculum.

12.2 Functional test results

Run 2 of the functional test produced readings of % of each gas in the offgas for the three fermenters (shown below). These results are described in section 7.1.3 of this document.

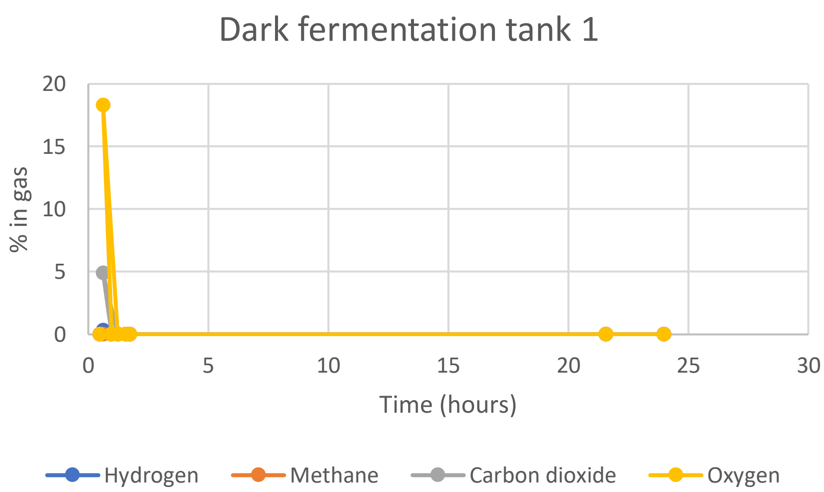

Figure 12: Hydrogen production in run 2, fermenter 1.

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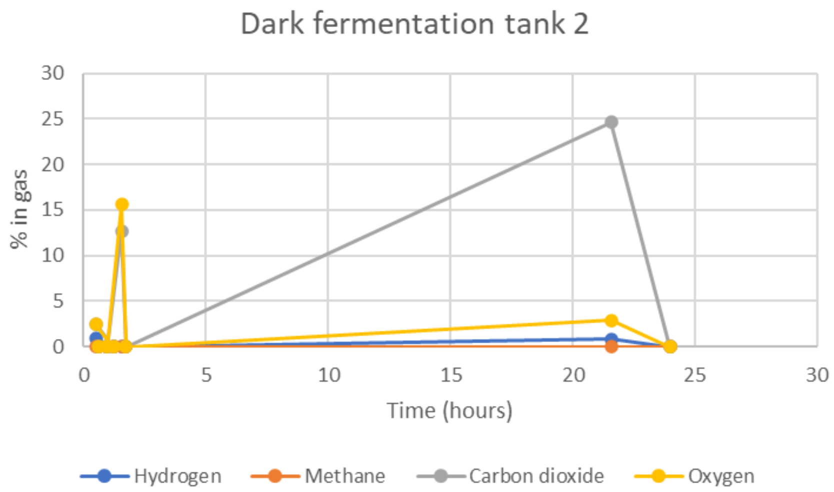

Figure 13: Hydrogen production in run 2, fermenter 2.

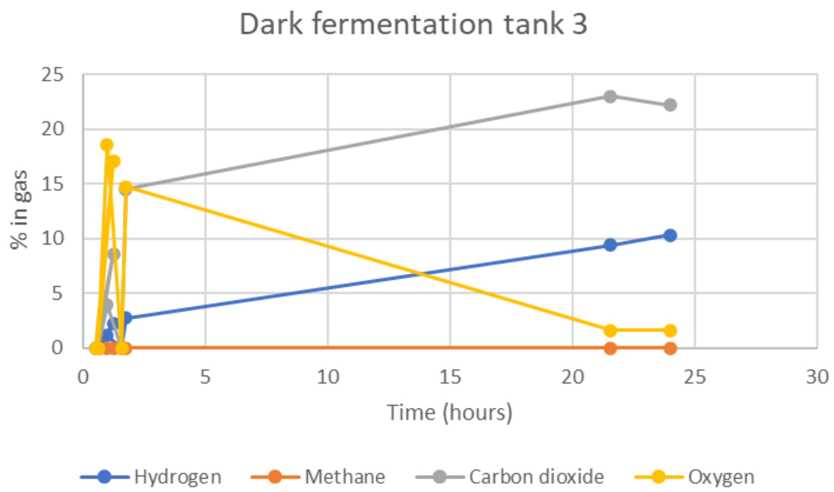

Figure 14: Hydrogen production in run 2, fermenter 3.

13 Appendix 4: Key learnings

13.1 Functional & Performance tests

13.1.1 Acidic feedstock

Hydrogen fermentation requires a lower PH than traditional biogas production. The acid environment was very attritional on emersion heating and probes, resulting in failures. Once the heating was replaced with externally mounted trace heating the problem was alleviated.

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13.1.2 Pumps

Pumps were the most common source of system shut down. Either because of blockage or insufficient flow rate causing an overflow or overheat. The pump specifications will be reviewed for the commercial demonstrator. Provision will allow be made for spare pumps to enable switch outs.

13.1.3 Motors

The study proved that the feed tanks, Dark Fermentation tanks and biogas digesters all require motorised direct drive paddle mixing. Due to the dry matter concentration in the feedstock, recirculation mixing proved inadequate at ensuring effective homogenization within the tank.

13.1.4 Particle size

The feedstock is a combination of OFMSW slurry and fibres. It was cavitated to blend the dry matter and reduce the particulate size. This was beneficial in improving the pumpability of the material which reduced blockage. It also homogenized the soup and exposed a larger surface area to bacteria during the fermentation phase, making more hydrogen available.

13.1.5 Batch vs continuous feeding

The switch from a batch process to a continuously fed solution was the most technically challenging aspect of the research. The results showed that Hydrogen rose as Oxygen was removed from the Dark Fermentation tank. Within batch manufacture the tank was filled, sealed, and injected with nitrogen to dispel oxygen. With the continually fed manufacturing process the tank is never fully sealed as feedstock is continually added and each new batch naturally contains Oxygen. This was overcome by changes to the mixer protocol, pump speeds and inlet valve. In the demonstrator version it is recommended to seal the feed and mixer tanks to minimise the opportunity for additional oxygen ingress.

13.1.6 Oxygen ingress

To remove the potential for oxygen ingress we added a non-return valve after the feed pump. This also produced more predictable feed volumes.

13.1.7 Gas collection

We found that it was essential to add a condensate trap to the gas lines which had the dual purpose of collecting the condensate to protect the gas analyser and stop any overflow from the fermenter from going up the gas lines.

13.1.8 Blockages

For parts of the system that were not pumped (i.e., the overflow) it was essential to keep the gauge of the pipe as large as possible to ensure that blockages didn't occur.

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13.1.9 Heating & temperature control

The Dark Fermentation process temperature must be constant. The temperature reading was very dependent on mixing because of the thickness of the substrate in the fermenter. Overheating would occur without efficient mixing to spread the heat. The immersion heaters tended to get crusted up with cooked-on solids. This was improved by good mixing but really required the heater to be cleaned once a week. When starting up, it was important to raise the temperature gradually to prevent overheating. In the scaled-up solution external heating methods are required and subject to budget the tank should be insulated of double walled to minimise heat loss.

13.1.10 Feed tank

Continuous feeding means that the tank is never empty so you can't tell exactly what the VS and TS of the feedstock is unless you test it daily.

13.1.11 Testing

The frequency of testing and the need to react to the lab results means onsite testing is preferable for most operational tests. This will require a more highly trained staff and a wider range of lab equipment and consumables in a subsequent phase.

13.1.12 Hydrogen Gas Analyser

A 10-channel syngas analyser was manufactured for this project and upgraded to include a Hydrogen gas sensor. The lead-time for this bespoke item was 16 weeks and should be factored into any future project plans.

13.1.13 Monitoring & control systems

The hydrogen production process is more sensitive than biogas production. There are more biological and environmental conditions (pH, temperature, and pressure) being manipulated. This requires a higher frequency of lab samples and data point monitoring to enable micro adjustments to be made. Wherever possible/practical any scaled up solution should incorporate Scada integrated sensors with automated control routines or operator alerts.

13.1.14 Data logging & reporting

The Dark Fermentation project implemented an Operator's Log which sets out the information that should be collected daily from the system, the samples to be taken and the tests to be done on the samples. The log is shared with all members of the team and discussed at weekly technical meetings. Many results were physically written, entered on a spreadsheet, and then collated. Going forward a fully digital recording system should be explored to reduce re-keying and link to dashboard reports. Further work should be done as part of a commercial demonstrator on KPIs (key performance indicators) for operators.

13.2 Project management

Despite significant planning, Alps underestimated the amount of project management and facilitation required in the first 3 months of the project. New recruits changed the dynamics of teams and extra facilitation was required to achieve optimal performance. There was also an experimental learning premium born by the project. Some activities simply took longer than anticipated because they had never been done before. There were also additional project meetings and brainstorming sessions required in problem solving and then communicating next steps within the team.

13.2.1 Daily scrums

The introduction of daily 15-minute scrums after 4 weeks proved beneficial in problem solving and managing risks. It also ensured momentum and focus on deliverables.

13.2.2 Actions minutes

Actions minutes after every meeting were beneficial in tracking next steps and establishing accountability. It also proved a simple audit trail for the project manager.

13.2.3 Microbial population inoculation

The research identified that microbial population is important in hydrogen synthesis (shown by the different results obtained from the functionally identical test runs). Inoculation of the feedstock with the appropriate bacterial species is integral to enhanced hydrogen output. The isolation, preparation and cultivation of inoculum should be considered as a standalone project work package in future. It may also have additional commercial applications which should be explored.

13.2.4 Purchasing

Purchasing was the most challenging aspect of the project. First choice equipment and parts were in short supply and prices inflated as a result. During the 4-month period from the application to the project's start, lead times, doubled or tripled. Equipment containing sensors or microchips went from 4 weeks to 16 weeks delivery. For a six-month project this was immensely challenging. This was overcome with the use of substitutes or used equipment. This did result in higher ongoing maintenance and increased fabrication time, but the research equipment was built to specification and performed its function. Supply chain issues persist but can be mitigated by the ordering of additional spare parts which will inflate future budgets or by extending project timelines.

13.2.5 Sub-contractors

The unique economic environment through spring and summer 2022 resulted in lots of changes in the availability of the project sub-contractors. During the festival season electricians and plumbers were being offered double rates so were simply unavailable. For projects of less than £5,000 many were unwilling to complete the BEIS forms required for subcontractor approval. The learning going forward on short deadline projects is perhaps to build a roster of 3 sub-contractors per trade and complete the BEIS forms in advance, so switching is simpler. For phase 2, an electrical engineer will be included on the project team, as it is the most used trade.

14 Appendix 6: Phase 2 Gantt chart

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15 Appendix 7: Data gap analysis after phase 1

The following items have been identified by the project team as gaps in the data or questions arising from phase 1 that require additional research or investigation.

- What is the maximum amount of hydrogen volume available before residual biogas production is reduced?
- What this the optimal VS and carbohydrate concentration in the feedstock for maximum hydrogen fermentation?
- Will increases in the solids loading produce more hydrogen and what is the point of diminishing returns in residual COD and process energy for heating and mixing.
- Will co-digestion of OFMSW with another carbohydrate rich feedstock like food waste increase hydrogen output?
- What is the impact of glycerol on the process? Will it increase hydrogen exponentially?
- What is the impact of economies of scale in process infrastructure on hydrogen output?