Department for Energy Security & Net Zero

Genesis Control Systems (UK) Ltd

HYDROGEN BECCS INNOVATION PROGRAMME: PHASE 2

FINAL REPORT

Environmental Power International (UK) Ltd. & Project Partners

21-02-2025

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

The project "*Pure Pyrolysis Refined*" is part of the Department's £1 billion Net Zero Innovation Portfolio which provides funding for low-carbon technologies and systems and aims to decrease the costs of decarbonisation helping enable the UK to end its contribution to climate change.

EXECUTIVE SUMMARY

This project was funded by the Department for Energy Security and Net Zero, under the Net Zero innovation Portfolio (NZIP) Hydrogen BECCS Innovation Programme Phase 2 (H2BECCS). The H2BECCS programme supported development and demonstration of innovative hydrogen from biomass with carbon capture solutions. Phase 2 follows the successful completion of the Phase 1 Feasibility Study in 2022, where the project team assessed the technical and economic viability of the proposed technology. Phase 2 aims to demonstrate the technology at scale, building on the findings from Phase 1 and advancing towards commercial implementation.

The Pure Pyrolysis Refined project represents a groundbreaking advancement in sustainable hydrogen production and carbon management, delivering an innovative, flexible system that achieves net-negative emissions while addressing critical environmental and economic challenges. At the core of this project is the integration of Environmental Power International (EPi)'s patented pyrolysis technology with advanced downstream gas refining processes, offering a cutting-edge solution for the clean energy transition. The graphical overview of the process is provided in Figure 1, which illustrates the key process steps and interactions within the system. The key objectives of the project are to maximise hydrogen production, reduce CO_2 emissions, optimise carbon capture, ensure process flexibility for a variety of feedstocks, minimise capital and operational costs whilst maintaining process efficiency, and minimising energy consumption through effective heat recovery.

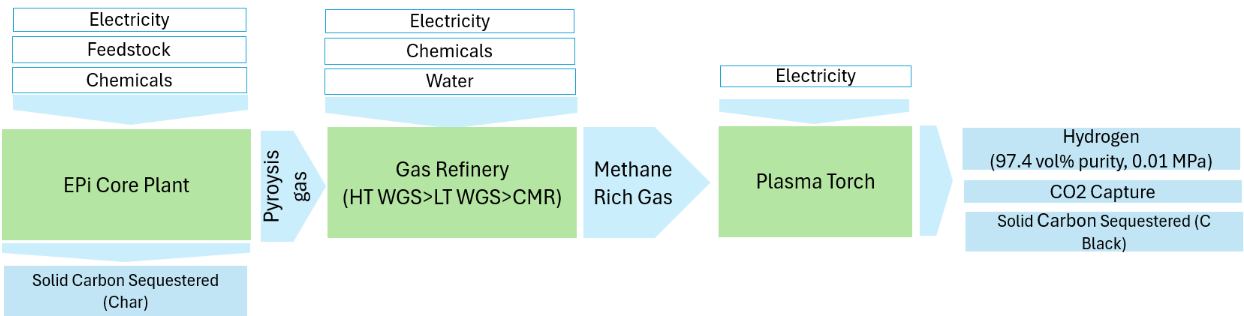

Figure 1 Illustrative process flow diagram - Hydrogen Production Pathway

A key milestone of the project is its ability to produce 191 kg/h of high-purity hydrogen and 547 kg/h of carbon black while maintaining net-negative carbon emissions of -0.805 t/h, depending on the application of outputs, such as using char and carbon black in cement/concrete production or inert underground storage, as stated in the Low Carbon Hydrogen Standard (LCHS) standard. These outcomes were validated through extensive trials and analysis at Imperial College London and EPi's development facility at PIMOT Laboratories, Poland (please refer to 3.1. Engineering Design), which ensured that the process could adapt to a wide range of feedstocks, including solid recovered fuel (SRF) and high-density polyethylene (HDPE). The trials demonstrated the system's robustness and flexibility in handling varying compositions and confirmed the longevity and effectiveness of catalysts selected for use in the catalytic reactors. Furthermore, high-fidelity modelling and pilot-scale testing supported the optimisation of energy use and process efficiency, resulting in a streamlined design that reduces both capital expenditure (CAPEX) and operational expenditure (OPEX) while maintaining superior performance.

The environmental benefits of the project are significant, marking a step-change in how waste is managed and utilised. The process converts waste materials into valuable products, such as hydrogen and carbon black, substantially reducing reliance on landfills and mitigating associated emissions. By capturing over 2,187 kg/h of CO_2 (net capture of 2,161kg/h of CO_2 when the 26kg/hr of CO_2 emissions are deducted), for every tonne of waste processed, the system achieves compliance with stringent net-negative emission targets while also contributing to a circular economy. The integration of advanced energy recovery systems further enhances the process's sustainability by achieving 67% heat reuse, significantly reducing the need for external energy inputs. This ensures that the technology aligns with global decarbonisation goals and supports the UK's commitment to net-zero emissions by 2050.

Economically, the project demonstrates impressive viability. The calculated LCOH stands at £41.6/MWh over a six-year period, with potential reductions to £34.6/MWh under favourable carbon pricing scenarios. This competitive cost is further enhanced by revenue streams generated from by-products such as carbon black and char, which are sold as commercial products. The modular design of the plant ensures scalability and adaptability, allowing it to be deployed across various locations to meet local energy demands efficiently. With plans to deploy 50 such plants across the UK, each capable of processing 85,000 tonnes of waste annually, the initiative is poised to collectively produce over 440,000 tonnes of hydrogen per year. These plants will significantly contribute to local energy supply, waste reduction, and economic growth, establishing the UK as a leader in sustainable hydrogen production.

Despite its remarkable progress, the project has faced challenges, including delays in regulatory approvals and funding uncertainties. Obtaining the necessary environmental licences proved to be a bottleneck, underscoring the need for more proactive engagement with regulatory authorities and contingency planning. To address funding challenges, efforts are being intensified to secure reliable investment sources, ensuring the timely mobilisation of resources for field operations. These experiences have provided valuable lessons that will inform future projects, including the importance of leveraging sites with existing licenses to expedite deployment and reduce project timelines. Additionally, while the project has successfully demonstrated its technology's potential through experimental trials and high-fidelity modelling, it has not yet been demonstrated in an operational environment. As presented in 3.1. Engineering Design, due to delays that prevented the plant from being installed and tested in a working environment before the project deadline, the installation and final testing of the plant will not be funded by the H2BECCS programme and will instead be supported by alternative private sources.

To address this, the project team is actively pursuing alternative funding opportunities to ensure continuity and to enable the transition to full-scale deployment. These efforts are vital to realising the broader impact of this transformative technology and to ensuring its contribution to global decarbonisation efforts.

The Pure Pyrolysis Refined project embodies innovation and sustainability, setting a benchmark for waste-to-energy conversion technologies. By turning waste into valuable energy products with minimal environmental impact, the project not only addresses pressing waste management challenges but also accelerates the transition to a hydrogen-based economy. With its modular and adaptable design, robust environmental performance, and economic feasibility, this revolutionary initiative is well-positioned to transform the clean energy landscape and advance global decarbonisation efforts for a more sustainable future.

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GLOSSARY/ABBREVIATIONS/ACRONYMS

Abbreviation	Definition
AR	Actual Realised
AVE	Average
BOM	Bill Of Material
C	Carbon
C&I	Commercial and Industrial
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamics
C-H	Methyl alkyl (Carbon-Hydrogen bonds)
CH_4	Methane
CMR	Catalytic Methanation Reactor
CO	Carbon Monoxide
CO_2	Carbon Dioxide
Cu-Zn	Copper-zinc oxide
C&D	Construction and Demolition waste
DESNZ	Department for Energy Security and Net Zero
EA	Environment Agency
EIA	Environmental Impact Assessments
EPD	Environmental Product Declaration
EPi	Environmental Power International Ltd.
excl	Excluding
FAT	Factory Acceptance Test
Fe_2O_3-Cr_2O_3	Iron-chromium oxide
FOAK	First-of-a-Kind
gCO_2e/MJ_{LHV}	grams of CO_2 equivalent per megajoule of lower heating value

Abbreviation	Definition
GHG	Greenhouse gas
gr	Gram
GR	Gas Refinery
gPROMS	General Process Modelling System software tool developed by Process Systems Enterprise (PSE)
GTL FT	Gas to Liquid Fischer-Tropsch
H	Hydrogen element
H_2	Hydrogen
H2BECCS	Hydrogen BECCS Innovation Programme Phase 2
HAR	Hydrogen Allocation Round
HAZOP	Hazard and Operability
HDPE	High Density Polyethylene
HGV	Heavy Goods Vehicle
HSE	Health, Safety, and Environment
HT LT WGS	High Temperature Low Temperature Water Gas Shift Reactor
ISO	International Organization for Standardization
K_2CO_3	Potassium carbonate
kg/h	Kilograms per hour
KPI	Key Performance Indicator
kWe	Kilowatt Electric
LCA	Life Cycle Assessment
LCOH	Levelised Cost of Hydrogen
LHV	Lower Heating Value
MCC	Motor Control Centre
MR	Methanation Reactor
MSW	Municipal Solid Waste
MWh	Mega Watt Hour
N	Nitrogen
NI	Nickel
NO_x	Nitrogen oxides
NPV	Net Present Value
O&M	Operations and Maintenance
OPEX	Operating Expenditure
PFD	Process Flow Diagram
P&ID	Piping And Instrumentation Diagram
PM	Payment Milestone
PSA	Pressure Swing Adsorption
PT	Plasma Torch
Q	Quarter
RAMS	Risk Assessment Method Statement
R&D	Research & Development
S	Sulphur

Abbreviation	Definition
SME	Small and Medium-sized Enterprises
SPSE	Siemens and Process Systems Enterprise
SRF	Solid Recovered Fuel
T	Temperature
T&S	Transport and Storage
TG	Target
TRL	Technology Readiness Level
UK	United Kingdom
VAT	Value Added Tax
WGS	Water Gas Shift
WP	Work Package
£	Great British Pound

1. BACKGROUND

EPi, is a UK-based international technology company, providing carbon negative fuels and renewable power generation which has developed and refined its patented pyrolysis technology over the past 20+ years. This innovative and patented technology is the cornerstone of EPi's operations. The organisation comprises several interconnected entities. For Hydrogen BECCS Innovation Programme Phase 2, EPi (UK R&D) Limited serves as the dedicated vehicle for research and development activities within the UK. It collaborates with EPi (UK) Limited, the principal commercial entity in the UK, which oversees staff employment and manages commercial contracts within the region. Throughout this document, the term EPi refers to the collective organisation. EPi was founded by Mark Collins-Thomas, who remains the lead Director across all EPi entities. The company has been privately funded by individual investors and continues to operate under private ownership.

Over an extended period of development, EPi's technology has been deployed in various locations, including Westbury (Wiltshire), Mitcham (Surrey), and Kula (Turkey). Currently, a commercial demonstrator plant is under construction, intended for deployment at one of two sites with the benefit of full planning consent.

Despite being an SME (Small and Medium-sized Enterprise) with fewer than 10 employees, EPi has established partnerships and collaborations with a wide range of organisations, providing the necessary resources and stability to deliver successful projects.

With increasing local and global pressure to reduce greenhouse gas emissions and develop sustainable energy solutions, there is an urgent need for scalable, cost-effective hydrogen production methods. This project addresses these challenges by integrating EPi’s unique advanced pyrolysis technology.

The aims of the Pure Pyrolysis Project are

- to achieve net-negative carbon emissions,
- maximise hydrogen yield, and
- improve the Levelised Cost of Hydrogen (LCOH).

The project integrates a high-temperature pyrolysis unit with a novel gas refining system, specifically designed for this project to optimise syngas composition, ensuring maximum hydrogen production with minimal carbon emissions.

This project builds on over two decades of research and development (R&D) in pyrolysis technology and leverages learnings from pilot plant trials conducted at Imperial College and PIMOT Laboratories in Poland.

The Pure Pyrolysis Refined project is part of the Hydrogen BECCS Innovation Programme Phase 2 (Demonstration Phase), funded by the UK Government. This builds on the successful completion of Phase 1 Feasibility study in 2022, which laid the groundwork for further development.

The project has been structured into eight work packages (WP), encompassing 72 deliverables across various fields including project management, plant design review and finalisation, procurement & manufacture, site construction and permits, mechanical and electrical installation, process optimisation and testing, knowledge dissemination and new business development. DESNZ funding for the project concluded in March 2025, by which point a total of 56 deliverables related to finalisation of design, testing, and manufacturing will have been completed. The remaining deliverables, which will focus on testing the complete system under continuous 3-shift operations, are scheduled for completion by the end of 2025 with private funding from alternative sources. This reflects the project's commitment to advancing toward operational readiness despite changes in funding arrangements.

The project aims to revolutionise hydrogen production by providing a sustainable, low-cost solution with significant carbon capture potential. The project is being developed in collaboration with Arup, Critical Path, Genesis Control, HiiROC, Imperial College, Siemens, Vertigo and WRM.

2. PROJECT OVERVIEW

The primary aim of the Pure Pyrolysis Refined project is to deliver a net-negative biohydrogen system that maximises hydrogen production and carbon capture while optimising the LCOH. This has been achieved through the integration of EPi's patented pyrolysis technology with a bespoke gas refining system.

Key objectives of the project include:

- Designing and constructing a scalable commercial demonstrator plant.
- Enhancing the efficiency of hydrogen production through advanced pyrolysis and refining processes.
- Demonstrating adaptability to variations in feedstock, market demands, and regulatory changes.

- Achieving significant carbon capture and sequestration to meet net-negative emissions targets.
- Delivering a flexible, cost-effective solution that supports the transition to sustainable energy markets.

The project is organised into 8 work packages, with a total of 72 deliverables, 56 of which were completed by March 2025. The activities referred to in Q2-Q4 2025 will be completed by the end of 2025 which will be funded through alternative private funding. Table A2 1 in **APPENDIX 2** demonstrates the comparison of the original and the final quarterly activities. Key milestones included:

- **Q2 2023:** Plant design review 1 and site lease approval.
- **Q3 2023:** Plant design review 2, procurement & manufacture stages 1 and 2, preparation of technical specifications for gas refinery system, preparation of Factory Acceptance Test (FATs) documents and preparation of social value programme and list of target SME's and entrepreneurs.
- **Q4 2023:** Stage gate review-1, plant design finalisation, design optimisation - energy recovery, procurement & manufacture stages 3 and 4, documentation preparation for cold and hot commissioning, technical specifications for all parts and equipment, preparation of FAT documents and options report on apprenticeships and placements.
- **Q1 2024:** Experimental validation of reactors, submission and award of planning permit, completion of site building design, documentation preparation for process optimisation & stabilisation, report on strategy for site visits during the operational phase.
- **Q2 2024:** Updating Bill of Material (BOM), site layout, process flow diagrams (PFDs), piping and instrumentation diagrams (PI&Ds), preparation of technical specifications for catalysts and consumables, procurement & manufacture stages 5 and 6, preparation of future community fund report.
- **Q3 2024:** Stage gate review – 2, procurement & manufacture stage 7, preparation of report on employment potential.
- **Q4 2024:** HAZOP (Hazard and Operability) study, procurement & manufacture stage 8, proof of manufacturing progress, FATs results, declarations of conformity, evidence of submission of Environmental Licence pack, preparation of commercialisation report.
- **Q1 2025:** Procurement & manufacture stages 9 and 10, social values outcome report and submission of final report.
- **Q2-Q4 2025:** Award of Environmental Licence, mechanical and electrical installation, cold and hot commissioning, process optimisation and stabilisation, Functional & Performance and Reliability Testing, process scale up, carbon life cycle assessment.

The estimated baseline cost of the project was £4.996,728.72. Following the removal of some of the sub-contractors via change requests, the baseline cost of the project was updated to be £4,948,453.71.

As of 31st of March 2025, the project has incurred a total expenditure of £3,558,809.42, which reflects the completion of the Manufacturing and Procurement phase. An increase in capital expenditure (CAPEX) has occurred due to a series of design changes. While these changes have raised the CAPEX, they are expected to contribute to cost reductions in the installation phase and potentially in OPEX savings over time. However, these OPEX savings have not yet been realised as these are expected to materialise during the installation, commissioning, and operational phases.

Due to delays that prevented the plant from being installed and tested in a working environment before the project contract end date, the remaining activities (Total budget £1,389,594.28, mentioned Q2-Q4 2025 above) will no longer be funded by the H2BECCS programme and will instead be supported by alternative private sources. As such Table A2 2 in **APPENDIX 2** demonstrates both the estimated and realised cost breakdown for the revised system delivered under the H2BECCS Project.

3. TECHNICAL AND COMMERCIAL REQUIREMENTS

3.1. Engineering Design

3.1.1. Evolution of Final Design

The development of the hydrogen production and carbon removal system and the finalisation of engineering design involved multiple stages of research, three-stage software modelling and validation through repetitive experimentation. These efforts ensured the refinement of the proposed innovation, addressing technical challenges and achieving a robust, high-performance solution.

The basic research and testing methodology led to final design involving extensive literature reviews and initial studies, performing experimental trials using a pilot-scale rig, developing and evaluating process design models before selecting the most suitable design and validating it through pilot plant testing, refining the process iteratively, and finalising the design for implementation. The sequence of events is demonstrated in Figure 2 below.

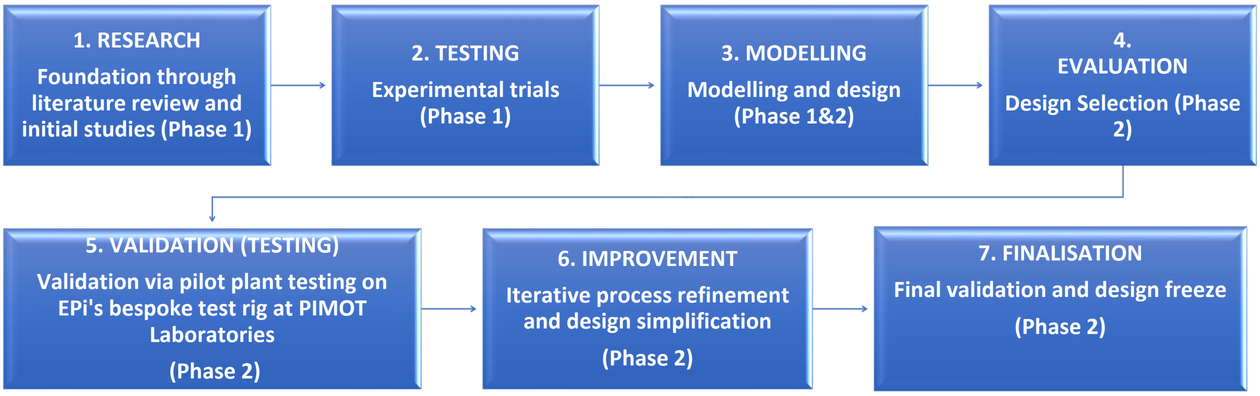


Figure 2 Block diagram: Research and testing methodology that led to final design

A comprehensive overview of the engineering design and development of innovation is provided below.

1. **RESEARCH: Foundation through literature review and initial studies (Phase 1):** The project commenced with a series of literature reviews and expert consultations to evaluate hydrogen production, carbon removal technologies, and the factors influencing the hydrogen production. During Phase 1, a comprehensive analysis of pyrolysis gas conversion processes was conducted. The key findings prompted the investigation of complementary technologies for potential integration with EPi's high temperature pyrolyser.
2. **TESTING: Experimental trials (Phase 1)**: A pilot-scale pyrolysis test rig, which was previously constructed to emulate the EPi pyrolyser's key operational principles, (please refer to Figure A3-1 1 in **APPENDIX 3-1**), was used to validate gas streams from the pyrolysis unit, produced from various feedstocks, ranging from SRF and willow wood (biogenic content by CV 84%) to SRF and waste HDPE plastics (biogenic content by CV 38%) mixture. Laboratory trials focused on finding the best feedstock mixture and operating temperature to obtain the pyrolysis gas for maximising hydrogen yield and carbon capture. The optimal feedstock was found to be a mixture of SRF and waste HDPE, with ideal operating temperatures ranging from 850°C to 1000°C across different parts of the reactor.
3. **MODELLING: Modelling and design (Phase 1&2):** Different configurations were developed to model downstream processes for integration with the pyrolysis process. A series of 15 detailed simulation studies using gPROMS™ (General Process Modelling System) were evaluated, incorporating WGS (Water Gas Shift) reactors, CM (Catalytic Methanation) reactors, CO_2 Removal and Regeneration, Amines Plant, membranes, Pressure Swing Adsorption, Gas to Liquid Fischer-Tropsch, Electrolysis etc. to identify the most suitable approach for producing high-purity hydrogen whilst capturing carbon in the form of carbon black and char.
   High-fidelity models were used to simulate the behaviour of the system under different configurations by using the gas compositions obtained from pyrolysis trials. Additional Computational Fluid Dynamics (CFD) simulations were provided by the plasma torch vendor to validate specific reactor and process configurations. Key objectives of modelling were to
   - Maximise hydrogen production,
   - Reduce CO_2 emissions and optimise carbon capture,
   - Ensure process flexibility for a variety of feedstocks,
   - Minimise capital and operational costs while maintaining process efficiency,
   - Minimise energy consumption (heat recovery).
4. **EVALUATION: Design Selection (Phase 2):** Based on the criteria above, EPi proposed its first configuration for a Gas Refinery Unit (GR) to be integrated with EPi's high-temperature pyrolysis system. The GR comprised three main processes:

a. CO_2 Removal and Regeneration Process: The syngas produced by the EPi pyrolyser is first treated in the CO_2 Removal and Regeneration process. In this process, carbon dioxide is removed using a hot potassium carbonate (K_2CO_3) solution under high pressure. The CO_2-rich solution is then regenerated, producing CO_2 gas with a purity of 99.96%. This purified CO_2 is then fed to a catalytic reactor for conversion into methane (CH_4), with some CO also being converted. The process involves the absorption of CO_2 from a gas stream, followed by the regeneration of the absorbent material to release the captured CO_2. The Absorption Column contains K_2CO_3 solvent (absorbent solution) which has an affinity for CO_2. CO_2 is captured from a gas stream using K_2CO_3 as an absorbent in an absorption column and later released in a regeneration column. In the absorption process, the CO_2 from the gas stream reacts with the K_2CO_3 solvent to form a soluble compound. The K_2CO_3 solvent contacts the gas, and CO_2 selectively reacts with the K_2CO_3 solvent, forming a chemical complex. After the absorbent (K_2CO_3 solvent) has captured CO_2, it is transported from the bottom of the Absorption Column to the top of the Regeneration Column. Under heat, the chemical complex breaks down, and the CO_2 is separated from the solvent.

b. 3-Stage Catalytic Reactors: Purified CO_2 from the combined Removal and Regeneration processes together with a portion of the syngas from the CO_2 Removal and Regeneration process is directed to a three-stage catalytic reactor in order to generate additional hydrogen and carbon dioxide to produce a methane rich gas.

c. Methane and Hydrogen Separation: The gas stream from the CO_2 Removal and Absorption Unit is passed through a polymer membrane to separate methane and hydrogen. Some of the hydrogen is redirected to the catalytic reactors as required for methane production.

The model predicted the following results from 800 kg/h of pyrolysis gas (derived from 1000 kg/h of feedstock which was a mixture of SRF and waste HDPE):

- **Hydrogen Production**: 192 kg/h (99.9% purity)
- **Carbon Black Production**: 541 kg/h
- **CO_2 Emissions**: 25 kg/h (2.5% of the feedstock weight), or approximately 130 grams of CO_2 for every kg of hydrogen produced.

5. **VALIDATION TESTING: Validation via pilot plant testing at PIMOT Laboratories, Poland (Phase 2)**: The modelled reactors were validated via pilot plant testing. All three catalytic reactors were tested on a pilot-scale facility specifically designed and manufactured to replicate actual scale and design, in order to evaluate the performance of the reactors and the catalysts used (please refer to figures from Figure A3-1 5 to Figure A3-1 15 in **APPENDIX 3-1**). Experimental trials demonstrated that:

- The reactors could fully accommodate gas compositions with higher CO_2 content than modelled expectations, ensuring robust performance under varying conditions.

- Various parameters, such as flow rates, H_2/CO_2 ratios, and cooling oil temperatures, were optimised.
- Experimental results confirmed catalyst longevity with individual reactor tube design matched to dimensions applicable to operational scale-up.

6. **IMPROVEMENT: Iterative process refinement and design simplification (Phase 2):** First stage trials demonstrated that the design could be simplified to address complexity concerns and in turn further reduce the OPEX. Key changes included:

- **Simplification of CO_2 management:**
  - The aforementioned CO_2 absorption and regeneration columns were removed from the design. This was validated via further trials at PIMOT laboratory.
- **Integration of Hydrogen Management:**
  - Excess hydrogen from the methanation step was effectively integrated into the process, eliminating the need for separate membranes for hydrogen recycling. As a result, the membrane was removed from the final design to reduce planned down-time to maintain another set of equipment, improving cost-efficiency.
- **Revised process configuration:**
  - Removal of CO_2 capture components and membrane reduced operational complexity and potentially maintenance requirements, improving OPEX.
  - The streamlined system maintained the output quality, while reducing the CO_2 emissions (total of non-biogenic and biogenic) from 0.057 tonnes/hr to 0.026 tonnes/hr. The hydrogen production decreased by only 1.2 kg/h (from 192 kg/h to 190.8 kg/h) a negligible impact compared to potential cost savings and reductions in CO_2 emissions.

7. **FINALISATION: Final validation and design freeze (Phase 2):** The final simplified design was validated through additional trials conducted on the test rig installed at PIMOT Laboratories with more complex gases. The test rig is designed to reproduce the exact operational conditions that the actual scale plant will be operated at (please refer to the test rig drawings in Figure A3-1 2-Figure A3-1 4 in **APPENDIX 3-1**). Experimental studies have demonstrated that catalytic reactors can effectively handle different compositions of gas and manage levels of CO and CO_2 present in the syngas, that are significantly higher than expected, ensuring efficient conversion into methane. The gas chromatograms from the experiments indicated that, without exception, no CO_2 was detected in the gas product. This demonstrates that the reactors very effectively eliminate CO_2 from the feed gas to the plasma torch. The system is designed to tolerate 20% fluctuation in the amount of CO and CO_2 in the syngas. This is achieved by controlling the water input to the reactors in relation to measured gas content. Figure A3-1 16 - Figure A3-1 23 in **APPENDIX 3-1** present the site lay-out, PFDs and P&IDs of the final design.

3.1.2. Final Design Description:

In the final design, the compressed pyrolysis gas is supplied to 3-stage catalytic reactors to convert the CO in the syngas into CO_2 and to react CO_2 and traces of CO with H_2 to form CH_4. The methane rich gas is then sent to Plasma Torch Units where C-H bonds are converted into hydrogen and carbon black.

Table A3-1 1, Table A3-1 2and Table A3-1 3 in **APPENDIX 3-1** present the detailed inlet and outlet gas compositions of reactors and PT units based on the high-fidelity model. Figure A1 1 in **APPENDIX 1** illustrates the process flow diagram for the hydrogen production pathway of the Pure Pyrolysis Refined project.

The EPi Pure Pyrolysis Refined plant is configured to produce the following products;

- Carbon char from EPi pyrolysis,
- Centrifuge cake from EPi pyrolysis,
- Carbon black from Plasma Torch
- Product gas containing mainly H_2 from Plasma Torch

Table 1 below demonstrates the mass balance achieved, based on the extensive modelling. The laboratory trials conducted further indicate that while 80% of the feedstock with biogenic content exceeding 25% (by CV) can be converted into pyrolysis gas, 10% of the input is converted into carbon char and 10% into centrifuge cake. Subsequent simulations run on gPROMS™ high-fidelity model illustrate that nearly 195.9 kg/h product gas (191 kg/h of which is hydrogen) and 548 kg/h carbon black are derived from 800 kg/h pyrolysis gas which in turn is produced from 1000 kg/h feedstock. The process is a closed circuit which does not release any CO_2 emissions direct to atmosphere.

Table 1 Mass Balance

Input, kg/h	
Feedstock	1000
Total In	1000
Output, kg/h	
Carbon Char	100.0
Pyrolysis Oil (Centrifuge cake)	100.0
Product Gas (97.4 wt% Hydrogen)	195.9
CO_2	0.0
Carbon Black	547.7
Water discharge	56.4
Total Out	1000

It must be noted that different operational conditions and/or variations in feedstock could alter the properties of carbon black and potentially impact its market value. However, since the process conditions were pre-established based on the input gas composition provided to the suppliers, the modelling exercise was conducted under fixed conditions. The variations in carbon black properties due to changes in temperature or feedstock were not modelled and will be accounted for following the trials.

During the engineering design phase, energy optimisation and heat recovery were carefully considered and integrated to enhance overall process efficiency and minimise energy consumption. The energy requirements of the process were optimised by utilising waste heat recovery systems. The model developed using gPROMS, incorporated mass and enthalpy balances, contributing to the overall mass and energy balance of the entire plant. Heat integration, designed and optimised through the model, allowed for energy recovery from all major gas streams and the internal reuse of this recovered energy within the plant.

Waste heat recovery modelling involved creating mathematical and computational models to analyse and optimise the recovery of heat from designed process. Waste heat is generated during activities such as exothermic reactions or from high-temperature by-products (e.g., steam, silicone oil, carbon black). Instead of dissipating this heat into the environment, waste heat recovery systems captured and repurposed it for electricity generation, fluid heating, or improved energy efficiency.

High-fidelity modelling of heat integration revealed that, in the absence of heat exchangers, the additional energy required via heaters would have been 1061 kJ/s. Through heat exchangers, 712 kJ/s of this energy is recovered within the system, reducing the need for external heat energy to just 349 kJ/s. This means 67% of the waste heat is effectively recovered, significantly surpassing the KPI (Key Performance Indicator) target of 25%.

The Technology Readiness Level (TRL) of the designed final system is assessed by taking into consideration the following factors. EPi has developed and tested five full-scale pyrolysis units, advancing the technology to a pre-commercial stage (TRL 7). The processes employed in the gas refinery (GR) system are established, proven technologies with extensive operational experience at full scale and high TRLs. The proposed PTs have been tested in actual environments using methane, thus achieving TRL 7. However, none of these technologies have been integrated and tested as a complete system. While the pyrolysis unit has been tested to produce syngas suitable for gas engines, it has not been operated to produce gas compatible with the downstream technologies proposed. Similarly, the GR processes and PTs have not been tested or operated with pyrolytic gas to produce hydrogen. As parts of the proposed system have been tested in a pilot plant using the actual feedstock in a relevant environment, the overall system was considered as TRL 6 at the beginning of the project. Due to delays experienced in the project, the technology prototype could not be demonstrated in an operating environment. However, EPi aims to complete the demonstration by the end of 2025. Supported by three detailed computer models and repetitive validation experiments, the overall system is expected to reach TRL7 by this date, provided that no significant issues arise during the installation, commissioning, or testing phases.

As discussed above, even though the system could not be demonstrated in an operating environment, the design, procurement and manufacturing of all parts and components are scheduled to be completed by the end of March 2025 leaving sufficient time for installation and demonstration to be completed by the end of 2025.

3.1.3. Regulatory Approvals and Permitting Challenges

The successful operation of the Pure Pyrolysis Refined project requires several key consents and regulatory approvals. The following outlines the steps taken to secure these permissions and the current status of applications:

- Site Lease Agreement: An in-principal lease for the project was secured on the 1st of June 2023, laying the groundwork for subsequent permitting activities.
- Planning Consent: A planning permit was granted on 27 March 2024. This marked a significant milestone in ensuring the project's compliance with local and national planning requirements.
- Environmental Permit: The application process for the Environmental Permit involved detailed coordination with the Environment Agency (EA).
  WRM Environmental Consultancy was appointed to manage the process and provide strategic guidance in navigating the regulatory framework. With their assistance, all necessary documentation was prepared, and the formal submission of the Environmental Licence Application was completed on 30 November 2024.
- Pre-Application Advice: To further streamline the permitting process, the project team applied for Pre-Application Advice and conducted a meeting on the 4th of December 2024. This process confirmed the following:
    - The application was granted priority status, ensuring completion within the requested timeframe (April 2025).
    - An initial review identified no significant obstacles to completing the permit by the target date.
    - Recognition that the EPi gas stream is likely to qualify as "End of Waste."
- However, following a review of the various factors, including time constraints, impacting the proposed use of the site at Great Blakenham,it was determined that continuing with the development of that site was no longer in EPi's best interests. It was concluded that developing an alternative site at Theale would be commercially advantageous. As a result, the application for an environmental permit from the EA was withdrawn. The reasons behind this decision were as follows:
    1. The PT technology now requires a larger footprint, and the Great Blakenham site cannot accommodate the full plant needed for a single EPi module's output. With plans to operate three modules, hydrogen generation at scale must now occur off-site.
    2. Senior process engineers at the EA, who had been helpful during the Pre-App support, were consulted to evaluate the best course of action for a potential relocation to an alternative site. The relocation to Theale was discussed, and similar support was confirmed. We also noted the potential to qualify for priority status due to pressures from leaseholders and funding partners.

These steps reflect the efforts toward compliance and regulatory engagement, essential for the timely and efficient progress of the project. Whilst substantial progress has been achieved, delays in obtaining Planning Consent and the Environmental Licence have impacted the project timeline. This has introduced uncertainties for key stakeholders, including DESNZ and funding partners. Despite these challenges, lessons learned from this process—such as the value of early stakeholder engagement and specialist consultancy support—are being applied to mitigate future delays.

3.2. Updated Cost Estimates

As described in detail in BEIS (2021)[1], the levelised cost of hydrogen (LCOH) is the discounted lifetime cost of building and operating a production asset, expressed as a cost per energy unit of hydrogen produced (£/MWh). It covers all relevant costs faced by the producer, including capital, operating, fuel and financing costs. The levelised cost of a hydrogen production technology is the ratio of the total costs of a generic/illustrative plant to the total amount of hydrogen expected to be produced over the plant's lifetime. Both are expressed in net present value terms. This means that future costs and outputs are discounted, when compared to costs and outputs today.

In light of the new standards introduced by LCHS, this report presents two scenarios for calculating LCOH. In Scenario 1, LCOH is calculated based on the assumption that both solid products, carbon black and carbon char, will be sold into their respective markets. Carbon char is assumed to be supplied to construction material producers at a value of 65 £/tonne, while carbon black is provided to the chemical industry at a higher value of 630 £/tonne. This scenario assumes that carbon black, when used in products such as tyres, inks batteries or higher efficiency electrical components, will not result in emissions. Once validated through repetitive testing during the trials, the end-use can be submitted for consideration as an additional Solid Carbon Permissible End Use, as outlined in the Standard Document[2]. The second scenario has been developed in response to the new limitations introduced by LCHS, where current regulations on solid carbon sequestration via gas splitting restrict permissible end uses to concrete/cement or inert underground storage. As a result, this scenario assumes that the only end use for the carbon solids will be in the construction materials industry, with the price for both products set at 65 £/tonne.

In this report, the LCOH is calculated by accounting for the NPV (Net Present Value) of the CAPEX, OPEX, revenues, and the cost of carbon sequestered. CAPEX covers the costs for pre-process plant, pyrolyser, syngas treatment & char unit, Gas Refinery processes, balance of plant, CH_4 Plasma Torch, as well as the project completion and handover.

OPEX is analysed under two main headings: fixed and variable costs. Fixed OPEX includes labour, operational overheads, and O&M costs. Additionally, as per the lease agreement put in place with the plasma torch providers, fixed operating costs also cover the lease fee and the O&M fees for the plasma torches. The variable OPEX includes the parasitic electricity costs for the overall integrated system and the consumables.

1 BEIS, (August 2021), "Hydrogen Production Costs 2021", Department of Business, Energy and Industrial Strategy
2 DESNZ (December 2023) Data Annex - Data for calculating Greenhouse Gas Emissions under the UK Low Carbon Hydrogen Standard, DA 54, pp:28-29

Variable costs also cover the royalty fee which is paid to the PT providers for every 1kg of hydrogen produced. Finally, while the levelised cost estimates do not consider revenue streams available from sale of hydrogen, this study takes into consideration the revenue streams available from gate fee, sales of carbon black and carbon char.

This is because, whilst the by-products of many other technologies attract additional costs from disposal, the carbon black and carbon char produced in this plant are commercial products, with their disposal route being through sales. However, it should be noted that establishing consistent commercial outlets for these products may present challenges, as highlighted in our detailed commercialisation report. Furthermore, variations in the properties of carbon black due to changes in operational conditions or feedstock composition could influence its market value, a factor that will be addressed in future trials. Once carbon black production begins, repetitive testing will be conducted to analyse its quality and stability. These analyses will provide a more accurate basis for determining the product's pricing and potential application areas. While these factors pose potential challenges, no insurmountable barriers have been identified in our planned deployment programme.

Similarly, with many other technologies the raw materials incur costs, however waste as feedstock leads to revenues. Therefore, the associated sales price can be considered as either negative variable cost or positive revenues. In this model, the sales revenues are accounted for as negative variable cost.

The feedstock to be utilised is determined as a mixture of SRF from C&D (Construction and Demolition waste) waste and waste HDPE. Initial discussions with the producers indicate that the revenue this raw material will amount to £85 per tonne[3]. The revenues from carbon black and carbon char are assumed as £630 and £65 per tonne respectively in Scenario 1 and £65 for both products in scenario 2 based on the outcome of preliminary discussions with the buyers[4].

Net amount of CO_2 sequestered is calculated as the difference between the total CO_2 emitted and total CO_2 sequestered. Net CO_2 sequestered amounts to 2,161 kg/hr and 12,964 kg/hr for single and 6 module plant respectively. Please refer to Figure A3-2 1 in **APPENDIX 3-2** for the total CO_2 emissions emitted and sequestered. Please refer to Table A3-2 1 for the assumptions made for the inputs used in the model in **APPENDIX 3-2**.

Net Present Value (NPV) analysis is carried out by combining the CAPEX and OPEX results, assuming a 25-year asset life and a discount factor of 10%.

The initial period is taken as one year for the operation of a single module followed by 5 years for the operation of full-size plant running a total of 6 modules. Therefore, the calculations are demonstrated as end of Phase 2 plus 5 years. The hurdle rate is applied based on data from BEIS (2021)[5]. The NPV and the LCOH are therefore demonstrated over 6 years in LCOH Phase 2 (1 year) + 5 years. Contribution of cost of all the related items to the LCOH is realised through calculating the NPV and associated levelised costs. Please refer to Table A3-2 4 and Table A3-2 5 in **APPENDIX 3-2** for the NPV and levelised cost results.

3 University of Suffolk, (Nov 2024), "Key Commercialisation Factors", p: 7
4 Ibid., p: 25-19
5 BEIS, (August 2021), "Hydrogen Production Costs 2021", Department of Business, Energy and Industrial Strategy, pp: 25-26

Subsequently, the levelised cost of hydrogen for both scenarios is calculated as follows: the LCOH in Scenario 1 is 41.6 £/MWh, while in Scenario 2 it is 82.7 £/MWh, over a 1+5 year period following the end of Phase 2.

The sensitivity of LCOH to carbon values is also demonstrated by running the same LCOH model on DESNZ's 2024 modelling traded carbon values. In order to assume the worst-case scenario, the baseline is calculated based on the "Low Sensitivity" scenario where the carbon prices are lower than the carbon prices cited in "Market Traded Carbon Values" and "Net Zero Strategy Aligned" scenarios. When the carbon values cited in these two scenarios are applied the LCOH in scenario 1 reduces to 37 £/MWh and 34.6 £/MWh, for Market Traded and Net Zero Strategy Aligned respectively over 5 year-period, following completion of 6 module plant installation and commissioning. The LCOH in Scenario 2 reduces from 82.7£/MWh to 78.2 £/MWh Market Traded strategy and 75.8 £/MWh for the Net Zero Strategy Aligned approach, over the same period. The results are demonstrated in the Table below and the carbon values are cited in the **APPENDIX 3-2**.

Table 2 LCOH for three different carbon Values in Scenarios 1 and 2

	LCOH (£/MWh) Phase 2 (1 year) + 5 Years Low Sensitivity	**LCOH (£/MWh) Phase 2 (1 year) + 5 Years** Market Traded Carbon Values	**LCOH (£/MWh) Phase 2 (1 year) + 5 Years** Net Zero Strategy Aligned
Scenario 1	**41.6**	**37.01**	**34.6**
Scenario 2	**82.7**	**78.2**	**75.8**

To assess cost performance, a comparison can be made with the recent government funding mechanism (HAR1) which was introduced to bridge the operating cost gap between low-carbon hydrogen and high-carbon counterfactual fuels. The 11 successful projects were awarded at a weighted average strike price of 241£/MWh (around 9.50 £/kg)[6]. The LCOH calculated in Scenario 1 equates to 1.60 £/kg, and 3.30 £/kg in Scenario 2. The percentage improvement from the underwritten cost is 83% in Scenario 1 and 65% in Scenario 2, making the hydrogen produced by this system highly competitive in the market. This could potentially enable market penetration or profitability even without significant financial support, demonstrating technological advancements and cost reductions in hydrogen production, while aligning with broader goals for the green energy transition.

$$\text{Scenario 1 Improvement Percentage} = \frac{(9.49 - 1.60)}{9.49}\ x\ 100 = 83.2\%$$

$$\text{Scenario 2 Improvement Percentage} = \frac{(9.49 - 3.30)}{9.49}\ x\ 100 = 65.2\%$$

It should be noted that the LCOH is calculated taking into account prices determined based on the characteristics of products identified through lab results and modelling exercises. The operational expenses are also estimates derived from historical operations conducted on EPi's R&D plant and discussions with the other technology

[6] S&P Global, "UK offers first green hydrogen production contracts to HAR1 projects", UK offers first green hydrogen production contracts to HAR1 projects | S&P Global

users. Additionally, the mass balance, and consequently the throughput and output amounts, are also based on the modelling results. Therefore, any changes to these values following the 3-shift trials could alter the costs reported in this section.

3.3. Demonstration and Testing Results

The Demonstration and Testing Results section highlights the outcomes of the pilot-scale operations, showcasing the system's performance, reliability, and alignment with the project's objectives, forming the foundation for commercialisation of the technology. The tests conducted in the project were designed and executed in accordance with the Test Plan submitted, which complies with the requirements of the UK LCHS. The experiments were carefully planned to achieve the specified objectives required by the project. They were carried out at pilot-scale facilities designed to operate under actual plant conditions, and the data obtained was used to validate the modelling results and the final system design. One of the primary goals of these tests was to verify whether the reaction conditions and catalysts were consistent with the designed model and met the LCHS requirements.

Key requirements of the LCHS and the actions taken to comply with the requirements have been summarised in Table in 3.4. Updated Carbon Life Cycle Assessment of the Technology. The measurements to be taken and the corresponding reporting timelines, as per the LCHS standards, are clearly outlined in Table A3-3 1 and Table A3-3 2 in the **APPENDIX 3-3**.

3.3.1. Performance Metrics and Economic Viability in Phase 2 Demonstration

The project used specific quantitative performance metrics throughout the Phase 2 demonstration. These metrics included hydrogen yield, emission reductions, efficiency improvements and technology availability. These key performance indicators were framed within relevant economic parameters, meaning that the performance metrics (such as hydrogen yield, efficiency, or reduction in emissions) were considered and assessed in relation to the economic factors that influence the project. The factors that are taken into consideration to achieve the performance metrics are as follows,

- **Cost-effectiveness**: EPi has reviewed the design repetitively and conducted several modelling studies to ensure that design was simplified and became more energy efficient. As discussed below, EPi set a KPI to recover more than 25% of the heat losses and exceeded its target, which will assist in reducing cost of electricity to be utilised for power input. Design reviews and experiments also demonstrated that some of the reactors could be removed, rendering the plant lean, and therefore assisting in reducing the time required for maintenance and increasing the operational hours. Several trials were also conducted on pyrolysis of different feedstock and the Gas Refinery system to ensure that the quality of methane rich gas, carbon char and carbon black could be enhanced to increase the sales value of these products. As discussed in 3.2. Updated Cost Estimates , EPi set a KPI target for LCOH to be below 86 £/MWh. The LCOH is calculated at 41.6 £/MWh in scenario 1, significantly below the set target and 82.7 £/MWh in scenario 2 which still meets the target, despite the full potential of carbon black not being realised due to existing regulations which impose limits on the end-use of this product.

- **Finances**: Extensive financial modelling has been undertaken over the duration of both Phase 1 and Phase 2 of the H2BECCS project. Despite the rapidly changing cost of materials due to various global impacts on manufacturing industries in the UK, Europe and beyond, the complete process for the production of low carbon hydrogen has been shown to be financially viable. The deployment of the technology across a broad spectrum of market sectors is not only commercially viable with full recovery of capital within relatively short time frames, but the practical aspects of the technology mean that the number of opportunities for commercial operation with rapid recovery of capital are manifold. Many alternative processes are dependent upon a single revenue stream. The EPi technology is designed to be flexible, to move seamlessly across multiple market sectors regardless of the pressures which could arise from increasingly volatile market conditions.

  As an example of the competitive commercial positioning of a typical 6-module EPi plant, processing approximately 52,000 tonnes per annum of mixed commercial waste, the following financial indicators are presented. All capital and operational costs, including the production of hydrogen using the HiiROC plasma torches, have been incorporated into the financial modelling. The income figures used are based on conservative net income estimates derived from the various output streams produced. These include £6 per kg for hydrogen, based on the assumption that securing support for an elevated HAR Strike Price (currently £9.49 per kg) may not be possible, and, due to uncertainties surrounding the quality of the carbon black, it has been priced at the same rate as carbon char, at a nominal £65 per tonne. This pricing allows access to the market for blending the char into a variety of construction materials, a readily accessible market, though one that provides lower levels of income compared to many alternative markets under consideration. Finally, a relatively low-price band of £65 for carbon credits has been selected, as this places the project within an easily accessible income range for the newly established trading mechanism. Despite basing the financial models on these lower income streams, the project is projected to recover capital within four years of commencement of operations.

- **Market factors:** Market penetration is one of the key parameters that has been considered throughout the design process. Pure Pyrolysis Refined has a robust business model in that it has a number of potential income flows in addition to hydrogen, namely Gate Fees, carbon Char, carbon black and carbon credits. This reflects the fact that the technology has multiple functions; waste disposal, hydrogen production, solid carbon production and/or carbon sequestration.

  As mentioned in this report, the process has a low LCOH. Further testing and analysis of the solid carbon outputs are needed to determine optimal uses and explore additional value through further processing. A comprehensive testing plan has been prepared to identify commercial opportunities, assess required specifications, quality standards, and pricing strategies for emerging markets.

3.3.2. Comprehensive Testing, Validation, and Key Performance Achievements in Phase 2

Along with considering the economic factors, EPi aimed to enhance confidence in the system by adopting a repetitive testing approach, where tests are validated by accredited laboratories and institutes, while finalising the overall system design.

Figure 3 Pyrolysis Pilot Plant

Pyrolysis trials were conducted in a pilot plant (Figure 3) which was specifically created to emulate certain aspects of the EPi pyrolyser during Phase 1. Gas Refinery system tests were carried out at PIMOT laboratories, Poland (Figure 4) using EPi's purpose-built laboratory test rig. (please refer to Figure A3-1 1- Figure A3-1 4 in **APPENDIX 3-1** to see the drawings of the pilot plants).

The pyrolysis trials conducted during Phase 1 used various feedstocks, including SRF, willow wood (biogenic content by CV 84%), and HDPE plastic waste (biogenic content by CV 38%). These trials focused on determining the optimal feedstock mixture and operating temperature for maximising hydrogen yield and carbon capture. Test results included elemental analysis (C: Carbon, H: Hydrogen, N: Nitrogen, S: Sulphur), moisture content, ash content, and energy content of the feedstock and char. Gas compositions were determined via gas chromatography. Additionally, mass and energy balances were calculated for each trial. The results were used to further refine the system design and confirm the feasibility of the chosen feedstocks for the intended process. All test results were presented in Table A3-3 - Table A3-3 8 in **APPENDIX 3-3**. While this work was conducted during Phase 1, it complements this report by providing a foundational understanding of feedstock performance and syngas composition, which provided input to Phase 2 system design and validation process. Trials confirmed that feedstock composition (oxygen content and C-H ratio) significantly affects gas composition. Pyrolysis of high-oxygen feedstock (biomass, paper, wood) produces gas with low CH_4 and high CO due to methane dry reforming and partial oxidation. In contrast, feedstock with higher plastic content yields more H_2 and CH_4 but less CO and CO_2. These variations in syngas composition influence system performance and hydrogen production. Low CH_4 and high CO syngas require increased energy input to drive water-gas shift reactions, as more CO must be converted to H_2. This may necessitate adjustments to operating conditions, such as higher steam-to-carbon ratios or increased catalyst loading, to maintain efficiency. Conversely, higher CH_4 content syngas can reduce energy demand and streamline hydrogen production processes, though the H_2 yield will vary based on feedstock composition.

Temperature also influences product distribution and gas composition. Lower temperatures favour char and oil production, while higher temperatures increase gas yield, hydrogen content, and gas energy.

In conclusion, CH_4-rich syngas with minimal CO and CO_2 can be achieved using low-oxygen, plastic-rich feedstock and high pyrolysis temperatures. This is favourable for hydrogen production processes that rely on catalytic reforming and/or methanation, as the reduced CO_2 content minimises carbon management challenges, and the higher CH_4 concentration improves the efficiency of downstream reactions and maximises hydrogen yield.

This Phase 1 work provides crucial insights that supported the development and refinement of the GR system during Phase 2, ensuring that the findings and design principles align with the scope and objectives of the Phase 2 funding.

The gas refinery system was validated through pilot-scale experiments conducted at EPi's facility at PIMOT laboratories, Poland during Phase 2, ensuring the trials were based on gas composition data from the trials. At PIMOT laboratories, reactors' performances were tested specifically regarding gas composition, flow rates, reactor dimensions and catalyst performance. In the first stage, testing of a single catalyst validated its use in the third catalytic reactor. In the second stage two different catalysts were tested in the first and second reactors. The reactor design was adjusted based on test results, reducing the bed height of the reactor, and adding a steam injection system to the third-stage reactor.

Figure 4 Gas Refinery Pilot Plant: Reactor, main heater, air cooler

Experimental test results confirmed that the catalysts for all three reactors performed as expected. These catalysts achieved the required conversions and selectivity within their optimal operational temperature ranges, ensuring their longevity in the commercial plant. Key findings showed that the catalysts would remain operational and maintain the desired conversion and selectivity through gradual increases in temperature and steam injection rates. The reactors' gas outputs (please refer to Tables Table A3-3 9 - Table A3-3 11 in **APPENDIX 3-3**) were in line with the modelled predictions, confirming that the system would perform efficiently when scaled.

A total of 56 experiments were conducted for three reactors. These tests validated the reactor designs, including actual scale vessel dimensions, flow rates, and catalyst performance.

A series of 16 additional trials were conducted using more complex gases, which further validated the simplified final design (please refer to Table A3-3 12 in **APPENDIX 3-3**). The results from these tests indicated that the system will maintain effective operation with fluctuating syngas compositions, confirming the robustness of the system. The reactor efficiently converted CO_2 into methane, with no CO_2 detected in the final gas product. This result confirms that the reactor is capable of eliminating CO_2 from the feed, achieving the required methane production for downstream applications such as plasma torch units. The system is designed to tolerate up to a 20% fluctuation in CO and CO_2 content in the syngas, managed through controlled water input.

The comprehensive testing and validation of the reactors, catalysts, and gas composition handling have confirmed the system's effectiveness and alignment with the initial design model. The project successfully demonstrated that the reactors can achieve the required conversions and selectivity over their expected lifetimes, providing confidence in the scale-up of the system for commercial hydrogen production. These tests serve as a crucial milestone in ensuring the efficiency, sustainability, and economic viability of the system, whilst meeting the outlined performance metrics.

The performance indicators demonstrate significant achievements based on pilot-scale trials and validated high-fidelity modelling with many values comfortably surpassing their targets as presented in Table below. These results suggest that the system is designed more efficiently than initially anticipated. The methodology behind the target setting involved a thorough review of industry benchmarks, expert consultations, and the performance capabilities of the technology at earlier stages, specifically based on the results of previous trials. Nevertheless, the outcomes indicate that our assumptions were on the cautious side. There are several key reasons why many KPIs exceeded their targets. First, the optimisation of the pyrolysis process (both feedstock mixture and temperature regime) likely contributed to higher conversion rates. Additionally, successful modelling and integration of GR system to pyrolysis system contributed to the higher-than-expected hydrogen production and purity, as well as the improved LCOH. The effectiveness of the GR design also played a role in surpassing expectations for CO_2 capture and achieving net-negative emissions. These results highlight a promising trajectory for the project. However, further analysis will be essential to understand the factors contributing to the results that exceeds the KPI targets, which will help us refine future targets and align expectations. Observing the system's performance in a real operational environment will be crucial for evaluating its practical effectiveness and ensuring its robustness under actual conditions.

Table 3 Key performance indicators of the project

KMI	Performance Indicators	Unit	Actual Realised	Target	Status
Reduce the cost of hydrogen production through pyrolysis of material with biogenic content higher than 25% (by CV) while achieving net negative emissions.	**KPI-1** Feedstock biogenic content	%	38	>25	Green
	KPI-2 Feedstock to Pyrolytic Gas Conversion	%	80	>55	Green
	KPI-3 Feedstock to Char Conversion	%	10	>8	Green
	KPI-4 Pyrolytic Gas to H_2 Conversion	%	26	>15	Green
	KPI-5 Pyrolytic Gas to Carbon Black Conversion	%	74	>60	Green
	KPI-6 Carbon Char Mass	kg/h	100	<250	Green
	KPI-7 Carbon Black Mass	kg/h	547.7	>370	Green
	KPI-8 Hydrogen Mass	kg/h	191	>125	Green
	KPI-9 H_2 purity	%	97.4	>90	Green
	KPI-10 CO_2 emissions released	kg/h	9	<550	Green
	KPI-11 Total CO_2 captured & sequestered	kg/h	2187	>1500	Green
	KPI-12 Net CO_2 Emissions	t/h	-0.805	<0.7	Green
	KPI-13 LCOH	£ / MWh	41.6	86.8	Green
	KPI-14 Continuous Operating hours	hours	-	>1250	Red
	KPI-15 Availability	%	-	>65	Red
	KPI-16 Recovery of Waste Heat	%	67	>25	Green
	KPI-17 TRL	-	6	8	Amber

Legend	
Green	Target Achieved or Exceeded
Amber	Partially Achieved or Progressing
Red	Target Not Achieved or Below Expectation

3.4. Updated Carbon Life Cycle Assessment of the Technology

The UK LCHS is a framework established to assess and certify hydrogen production pathways, ensuring that they meet the necessary environmental, safety, and sustainability criteria in line with the UK's carbon reduction goals. The standard provides a set of guidelines to assess the carbon intensity and lifecycle impacts of hydrogen production, as well as its health, safety, and sustainability considerations. The concept of Standard Compliance applies to consignments rather than the hydrogen production facility itself. For a consignment[7] to be compliant, it must meet the criteria to be considered low carbon hydrogen. Claims of standard compliance cannot be made until the hydrogen production facility starts producing consignments. Prior to the start of production, only likely standard compliance can be claimed (such as proving eligibility for government subsidy schemes). Since hydrogen production of this project has not started yet, it can only be stated that compliance with the standard is likely at this stage.

Compliance with the standard consists of two main components: "consignment" compliance and "hydrogen production facility" compliance.

For a consignment to be considered compliant, it must:

- Have a final greenhouse gas (GHG) emission intensity of 20 gCO_2e/MJ_{LHV} or less.
- Be produced at a compliant hydrogen production facility.

For a hydrogen production facility to be compliant, it must:

- Utilise an eligible hydrogen production pathway.
- Meet evidence and sustainability requirements for both inputs and outputs to the facility.
- Produce monthly reports on the emission intensities of consignments, as well as risk reduction plans for fugitive emissions, and an annual fugitive emissions report.
- Implement a data collection and monitoring procedure in collaboration with delivery partners.

To ensure compliance with the LCHS, the following parameters and requirements must be carefully tracked and assessed as presented in Table which provides a concise overview of the key parameters, thresholds, and actions needed for compliance with LCHS.

[7] An amount of Hydrogen Product which shares the same Environmental Characteristics (including GHG Emission Intensity) within a Reporting Unit. Discrete Consignments are determined by the feedstock(s) for Pathways with a feedstock, or by the energy Input(s) for Pathways without a feedstock. Source: UK Low Carbon Hydrogen Standard: Greenhouse Gas Emissions Methodology and Conditions of Standard Compliance

Table 4 Key parameters, thresholds, and actions needed for compliance with LCHS

Category	Parameter	Threshold/ Requirement	Actions	EPi Actions
GHG Emission Intensity	Final GHG Emission Intensity	≤ 20 gCO_2e/MJ (LHV basis)	Calculate lifecycle emissions using LHV. Include all emission categories (feedstock, energy, process, fugitive).	Calculate GHG emission intensity for each consignment once the operations start
Production Pathway	Eligible Hydrogen Pathway (Electrolysis, Fossil / biogenic gas reforming (with CCS), Gas splitting producing Solid Carbon, Biomass / waste gasification)	Confirm pathway complies with Chapter 4	Ensure process includes pyrolysis, GR processes. Provide methodology evidence.	EPi's project consists of eligible hydrogen production pathway (please refer to 3.1. Engineering Design for process description)
Solid Carbon Outputs	Carbon End Use	Meet requirements of Paragraph 5.57	Verify storage/utilisation of solid carbon. Avoid offsets for sequestration.	Demonstrate the end-use of solid carbon, ensuring compliance with the current regulations, which limit permissible end uses to concrete/cement or inert underground storage, as specified in paragraph 5.57 and DA.54 of the LCHS Data Annex. Note that these regulations may be subject to change in future versions of the standard. Record and report accurate data on the amount of solid carbon produced and how it is used or disposed of.

Category	Parameter	Threshold/ Requirement	Actions	EPi Actions
Fugitive Emissions	Hydrogen Leakage	Minimise fugitive emissions as low as reasonably practical	Prepare Risk Reduction Plan (pre-operation). Provide Annual Emissions Report.	Identify potential sources of leakage throughout the production and storage process. Implement engineering controls such as sealing and improved materials to prevent leakage. Use advanced monitoring technologies (such as gas detectors, infrared cameras) to detect leaks early and prevent them from becoming significant. Regularly maintain equipment, pipelines, and valves to reduce the chances of leaks due to wear and tear. Estimate and quantify the potential CO_2 emissions from fugitive sources in grams of CO_2 equivalent per year (gCO_2e/year). Prepare Risk Reduction Plan (pre-operation). Provide Annual Emissions Report.
Fugitive Emissions	CO_2 Leakage	Capture and account for fugitive CO_2 emissions	Quantify potential emissions in gCO_2e/year.	Identify potential sources of leakage throughout the production and storage process. Implement engineering controls such as sealing and improved materials to prevent leakage. Use advanced monitoring technologies (such as gas detectors, infrared cameras) to detect leaks early and prevent them from becoming significant. Regularly maintain equipment, pipelines, and valves to reduce the chances of leaks due to wear and tear. Estimate and quantify the potential CO_2 emissions from fugitive sources in grams of CO_2 equivalent per year (gCO_2e/year). Prepare Risk Reduction Plan (pre-operation). Provide Annual Emissions Report.

Category	Parameter	Threshold/ Requirement	Actions	EPi Actions
Biomass Feedstock	Biogenic Ratio and Sustainability	≥ 50% waste/residue feedstock by LHV (if biogenic used); Meet Chapter 6 sustainability criteria	Confirm feedstock certifications. Report carbon content and biogenic ratio. Ensure ILUC (Indirect Land Use Change) emissions are addressed.	Ensure using ≥ 50% Waste/Residue Feedstock by LHV. Ensure that the feedstock is sourced responsibly, does not contribute to deforestation, and has minimal environmental impact. Obtain certifications for the feedstock that confirm its sustainability and biogenic nature. Report the carbon content of the feedstock and the biogenic ratio.
Energy Inputs	Renewable Electricity (REGO)	Procure REGOs for renewable energy	Report energy sources monthly. Meet evidence requirements in Annex B and Annex C (if applicable).	Track and report the energy sources used monthly. If renewable electricity is used for the operations, then collect and maintain following documentation: Valid REGOs or other certificates of renewable energy use. Detailed records of electricity consumption. Verification or audit reports (if applicable)
Emission Categories	Materiality Thresholds	Account for all material emissions (feedstock, energy, process, fugitive)	Perform lifecycle analysis. Quantify all emissions, adhering to Paragraphs 5.72-5.80.	Ensure tracking and quantifying all material emissions associated with the operations (such as feedstock, process, energy etc.) Quantify all emissions. Conduct a lifecycle analysis (LCA).
Reporting	Monthly Consignment Reporting	Final GHG Emission Intensity and Raw Emissions split by category (every consignment)	Set up systems to track data per consignment. Create 30-minute reporting units.	Set up a data tracking system that records emissions. Set up automated systems or manual procedures to record emissions every 30 minutes, for example, using gas detectors or other monitoring tools to capture data in real time. Calculate GHG emission intensity for each consignment. Submit an annual fugitive emissions report that details any hydrogen or CO_2 leaks, monitoring results, and mitigation actions taken during the year. Submit an updated risk reduction plan annually including lessons learned.

Category	Parameter	Threshold/ Requirement	Actions	EPi Actions
Reporting	Annual Reports	Fugitive Emissions Report; Updated Risk Reduction Plan	Submit reports detailing compliance with emission thresholds.	Set up a data tracking system that records emissions. Set up automated systems or manual procedures to record emissions every 30 minutes, for example, using gas detectors or other monitoring tools to capture data in real time. Calculate GHG emission intensity for each consignment. Submit an annual fugitive emissions report that details any hydrogen or CO_2 leaks, monitoring results, and mitigation actions taken during the year. Submit an updated risk reduction plan annually including lessons learned.
Data Monitoring	Data Collection and Monitoring Plan	Establish robust monitoring systems	Develop DCMP with delivery partner. Implement real-time tracking of inputs, outputs, and emissions.	Create a detailed DCMP outlining the monitoring strategy, tools, and procedures for tracking all relevant data related to inputs, outputs, and emissions. The plan should cover data collection protocols, measurement techniques, and frequency of monitoring. Work closely with delivery partners to ensure the plan aligns with both operational needs and regulatory requirements. Implement real-time tracking systems that monitor key parameters such as feedstock inputs, energy consumption, and emissions outputs. Ensure the monitoring systems are integrated so that data on inputs, emissions, and outputs is captured simultaneously, ensuring consistency and accuracy across the operations.

Category	Parameter	Threshold/ Requirement	Actions	EPi Actions
Outputs	Hydrogen Production	Track production volume in tonnes and energy content (MJ LHV)	Ensure accurate mass balances and production records.	Measure and track hydrogen production, ensuring that production volumes are recorded in tonnes. Quantify the solid carbon produced per tonne of feedstock used in the process. Calculate the energy content of the produced hydrogen using its Lower Heating Value (LHV) in MJ. Asses the energy output per tonne of hydrogen produced. Keep accurate mass balances to ensure that all inputs, outputs, and energy content are correctly documented. Confirm compliance with any applicable carbon sequestration or end-use requirements for solid carbon outputs.
Outputs	Solid Carbon Conversion	Confirm compliance with carbon sequestration and end-use requirements	Measure tonnes of solid carbon generated per tonne of feedstock.	Measure and track hydrogen production, ensuring that production volumes are recorded in tonnes. Quantify the solid carbon produced per tonne of feedstock used in the process. Calculate the energy content of the produced hydrogen using its Lower Heating Value (LHV) in MJ. Asses the energy output per tonne of hydrogen produced. Keep accurate mass balances to ensure that all inputs, outputs, and energy content are correctly documented. Confirm compliance with any applicable carbon sequestration or end-use requirements for solid carbon outputs.

Based on the standard requirements stated in Table , the following key parameters must be calculated to ensure compliance with the standard.

1. GHG Emission Intensity (gCO_2e/MJ)
2. CO_2 emissions of the system (LCA) ($gCO_2e/year$)

Life Cycle Assessment (LCA) has been conducted to evaluate the environmental impacts of the Pure Pyrolysis Refined project (please refer to Figure A3-4 1and Figure A3-4 2 in **APPENDIX 3-4**).

This assessment defines a clear boundary for calculating the carbon footprint, focusing on the hydrogen production process from input material to final hydrogen output. It includes emissions from the conversion process, external power input, and carbon stored as carbon char and carbon black. Emissions from municipal solid waste (MSW) collection, transport, and SRF processing are excluded, assuming MSW is part of existing waste management. Carbon from the previous SRF lifecycle is also excluded, as SRF is treated as waste with zero value. The study follows an "attributional approach," using the best available data to detail assumptions behind the processes.

The DESNZ project requires hydrogen production from feedstock with at least 25% biogenic content (net CV), while minimising carbon emissions. The pilot plant has been tested with feedstocks containing biogenic content ranging from 38% to 84%, and the planned operations will use a mixture of SRF and waste HDPE with 38% biogenic content, meeting the project's criteria.

The total system carbon emissions are calculated as a sum of the carbon flows at each stage of the process. The carbon emissions from the process are:

1. Emissions from utilisation of the carbon char (assumed zero if not combusted)
2. Emissions from the release of CO_2 to atmosphere
3. Any scope 2 emissions caused by plant parasitic energy requirements
4. Stored emissions from the carbon char produced by the pyrolysis system and carbon black generated in plasma hydrogen production

There are a number of assumptions and limitations that are implemented within the carbon assessment model as presented in Table A3-4 1 in **APPENDIX 3-4**.

Plant availability is taken to be 7800 hours/year, and the plant is assumed to accept maximum 1 tonne/hour of SRF material. The model is based on one pure pyrolysis unit.

The feedstock to the pyrolysis process is a mixture of SRF and waste HDPE, (Note* SRF is produced from MSW by removing all inert matter and recyclable components).

Mass balances at each stage of the process were obtained based on results of tests conducted on the pilot plant and high-fidelity model gPROMS simulations:

- 0.800 tonnes of syngas are produced per tonne of SRF input
- 0.100 tonnes of char are produced per tonne of SRF input
- 0.196 tonnes of hydrogen are produced per tonne of SRF input
- 0.548 tonnes of carbon black are produced per tonne of SRF input
- 0 tonnes of purged CO_2 are produced per tonne of SRF input

The carbon content and biogenic fraction of the SRF were provided by Imperial College and Alfred H Knight Energy Services Ltd based on testing; however, it should be noted that any significant changes to the SRF composition could alter these figures. The carbon content of SRF is assumed to be 71.64% (by weight) with the biogenic carbon ratio estimated at 38% (by weight). The carbon content of the char, based on testing by Imperial College, is taken to be 51% by weight.

The carbon content of the syngas at each stage of the process was calculated from the component mass fraction, molar mass and number of carbon atoms of the component gases. The composition of the syngas at each stage of the process was provided based on testing from trial simulation runs of the process.

The energy content of SRF and carbon char were accepted as 37.76 MJ/kg and 17.6 MJ/kg respectively, based on results of tests conducted on the pilot plant.

The energy content of the syngas at each stage of the process was calculated from its component gases, with the calorific value of each component sourced from literature. The composition of the syngas at each stage of the process was provided based on testing from trial simulation runs of the process except pyrolysis gas composition, which was obtained from pilot trials.

The maximum parasitic electrical load of the process equipment (1 unit EPi core plant, Gas Refinery and 35 PT unit) was calculated to be 2188 kWe (installed power), and a 75% utilisation factor (equating to 1641 kWe electrical consumption).

The energy associated with processing MSW is not included as previously mentioned, as this is outside the boundary of this assessment. It is assumed that all electricity used in the plant is supplied externally from the grid as the actual plant will be running on the grid electricity. The carbon intensity associated with producing the catalysts used for the catalytic reactions is not accounted for in this assessment. However, the system design incorporates the selected catalysts, and their impact on the reactors is reflected in the mass balance.

Grid carbon intensity is taken from the HM Treasury Green Book Data 2023 consumption-based grid average carbon intensity for the industrial sector. The average grid carbon intensity was taken to be 0.136 tonnes CO_2/MWe.

Biogenic carbon emitted has been sequestered by organic material during its lifecycle and then is released to atmosphere. By this definition, biogenic emissions to atmosphere can be reported as neutral.

Biogenic carbon stored in solid carbon and char is sequestered by organic material during its lifecycle and can be reported as a negative emission, provided it is not combusted in the future. Char and carbon black are stored in silos before use. However, as per the current regulations, the permissible end uses that enable the use of the 'Solid carbon sequestration' term are limited to cement/concrete or inert underground storage. LCHS does not explicitly prohibit the use of char or carbon black for other purposes, but it specifies acceptable pathways such as use in cement/concrete production or inert underground storage, to meet the criteria for low-carbon classification. Use of char/carbon black in cement/concrete production contributes to carbon sequestration by locking the carbon in a stable, long-lasting material (concrete), effectively preventing its release into the atmosphere. This is considered a valid use because the carbon is not emitted as CO_2; instead, it is stored in a product with a long lifecycle, aligning with the goal of reducing greenhouse gas emissions. Similarly, inert underground storage involves the stable sequestration of carbon in geological formations or other secure underground environments where it will not react or release CO_2 into the atmosphere. Storing carbon in an inert state underground ensures that the carbon does not contribute to atmospheric greenhouse gas concentrations. It supports achieving net-zero emissions by removing the carbon byproducts from circulation in the biosphere. If char or carbon black is intended to be used for other purposes, it may still be permissible under LCHS[8], but it must be demonstrated that the pathway does not lead to significant CO_2 emissions during or after use and align with the overarching objective of reducing greenhouse gas emissions.

The key outputs from the carbon assessment are provided in tables below. Table presents the carbon mass flow rates at each stage of the pure pyrolysis process.

Table and Figure demonstrate the carbon dioxide emissions emitted or stored at each stage of the pure pyrolysis process.

Table 5 Carbon flow rate at each stage of process

Process Stage	Solid Carbon Mass Flow
Input	0.716 tonnes/hr carbon is input to the system with the SRF.
Stage 1 - Pyrolysis	0.546 tonnes/hr remains in the syngas and 0.051 tonnes/hr is stored in the char.
Stage 2 – 1st and 2nd Reactors	The syngas after the 1st set of reactors has a carbon content 0.545 tonnes/hr.
Stage 3 - 3rd reactor	The syngas entering the Plasma Torch has a carbon content of 0.546 tonnes/hr.
Stage 4 - Plasma Torch	0.546 tonnes/hr carbon is stored in carbon black.

Table 6 Carbon dioxide emissions at each stage of process

Process Stage	Carbon Dioxide Equivalent Emissions
Stage 1 - Pyrolysis	0.071 tonnes/hr of **biogenic** CO_2 and 0.115 tonnes/hr of **non-biogenic** CO_2 is stored in the carbon char.
Stage 2 - 1st and 2nd Reactors	No emissions at this stage.
Stage 3 - 3rd Reactor	No emissions at this stage.
Stage 4 - Plasma Torch	0.760 tonnes/hr of **biogenic** CO_2 and 1.241 tonnes/hr **non-biogenic** CO_2 is stored as carbon black.
Parasitic Energy	0.026 tonnes/hr of CO_2 is associated with grid electricity use to power the system.

The stored biogenic and non-biogenic CO_2 equivalents in the char and in the carbon black were calculated as below.

Char CO_2 equivalent mass flowrate (non-biogenic stored):

$$\text{Nonbiogenic Stored } CO_2 \text{ equivalent in char} = \text{Char C mass flow rate x } \frac{MMCO_2}{MMCarbon}\, x\,(1 - \text{SRF biogenic carbon fraction}) \times \%\text{char stored}$$

$$\text{Nonbiogenic Stored } CO_2 \text{ equivalent in char} = 0.051 \text{ x } \frac{44}{12}\, x\,(1 - 0.38) \times 1 = 0.115 \text{ t/h}$$

[8] UK Low Carbon Hydrogen Standard, Greenhouse Gas Emissions Methodology and Conditions of Standard Compliance, V3, December 2023, pp 31-32

Char CO_2 equivalent mass flowrate (biogenic stored):

$$\text{Biogenic Stored } CO_2 \text{ equivalent in char} = \text{Char C mass flow rate x } \frac{MMCO_2}{MMCarbon}\ x\ (\text{SRF biogenic carbon fraction}) \times \%\text{char stored}$$

$$\text{Biogenic Stored } CO_2 \text{ equivalent in char} = 0.051 \text{ x } \frac{44}{12}\ x\ 0.38 \times 1 = 0.071 \text{ t/h}$$

Where char C mass flow rate is the total mass flow rate of C char (t/hr): 0.051t/h, "$MMCO_2$/MM Carbon" is the molar mass ratio of CO_2 to carbon: 44/12, SRF biogenic carbon fraction is the fraction of carbon that is biogenic: 38%, %char stored is the percentage of char carbon stored as solid carbon: 100%.

Similarly, Solid carbon CO_2 equivalent mass flowrate (non-biogenic stored) is calculated as below.

$$\text{Nonbiogenic Stored } CO_2 \text{ equivalent in Carbon black} = \text{Carbon black C mass flow rate x } \frac{MMCO_2}{MMCarbon}\ x\ (1 - \text{SRF biogenic carbon fraction}) \times \%\text{carbon black stored}$$

$$\text{Nonbiogenic Stored } CO_2 \text{ equivalent in carbon black} = 0.546 \text{ x } \frac{44}{12}\ x\ (1 - 0.38) \times 1 = 1.241 \text{ t/h}$$

Solid carbon CO_2 equivalent mass flowrate (biogenic stored) is calculated as.

$$\text{Biogenic Stored } CO_2 \text{ equivalent in carbon black} = \text{Carbon black C mass flow rate x } \frac{MMCO_2}{MMCarbon}\ x\ (\text{SRF biogenic carbon fraction}) \times \%\text{char stored}$$

$$\text{Biogenic Stored } CO_2 \text{ equivalent in carbon black} = 0.546 \text{ x } \frac{44}{12}\ x\ 0.38 \times 1 = 0.760 \text{ t/h}$$

Where solid C mass flow rate is the total mass flow rate of C carbon black (t/hr): 0.546 t/h, "$MMCO_2$/MM Carbon" is the molar mass ratio of CO_2 to carbon: 44/12, SRF biogenic carbon fraction is the fraction of carbon that is biogenic: 38%, %carbon black stored is the percentage of carbon stored as solid carbon: 100%.

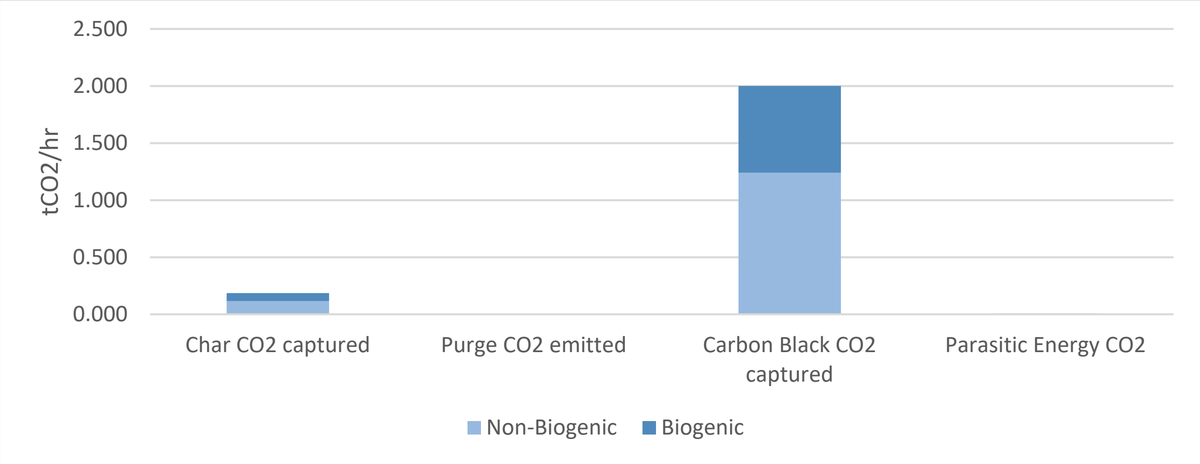


Figure 5 Carbon emissions from pure pyrolysis process

Table presents the calculation of total and net carbon dioxide emissions associated with the whole system (within carbon assessment boundaries set out previously), based on the results from Table . Figure indicates the net emissions from pure pyrolysis process.

Table 7 Total system carbon emissions

	Description	Value
Total emitted non-biogenic CO_2	Purged CO_2 (non-biogenic only) + grid emissions	0.026 tonnes/hr
Total emitted biogenic CO_2*	Purged CO_2 (biogenic only)	0.000 tonnes/hr
Total stored non-biogenic CO_2	Char + carbon black CO_2 (non-biogenic only)	1.356 tonnes/hr
Total stored biogenic CO_2**	Char + carbon black CO_2 (biogenic only)	0.831 tonnes/hr
Net CO_2 emissions	Total emitted non-biogenic CO_2 - Total stored biogenic CO_2	-0.805 tonnes/hr

* The biogenic carbon emitted has been sequestered by organic material during its lifecycle and then is released to atmosphere. By this definition, biogenic emissions to atmosphere can be reported as neutral.
**The biogenic carbon stored in solid carbon and char has been sequestered by organic material during its lifecycle. By this definition, sequestering the biogenic carbon then storing in char or Carbon Black can be reported as a negative emission, provided that the solid carbon is used in cement/concrete for construction or stored in inert underground storage, as permitted under LCHS guidelines.

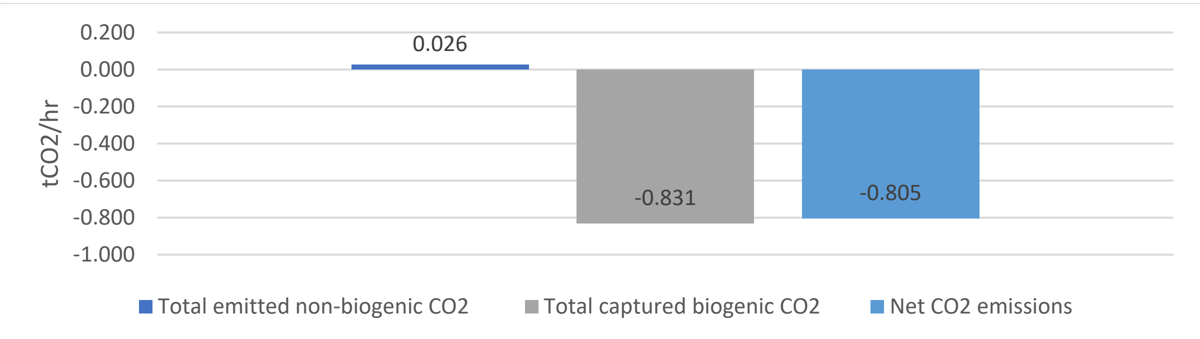


Figure 6 Net emissions from pure pyrolysis process

To sum up, the results of the carbon assessment show that EPi's pure pyrolysis process is found to release 0.026 tonnes/hr carbon dioxide emissions to atmosphere which is the total emitted non-biogenic CO_2.The process captures 2.187 tonnes/hr of carbon dioxide in char and carbon black, of which 0.831 tonnes/hr is biogenic and therefore can be treated as negative. Therefore, by this rationale, the process results in 0.805 tonnes/hour net negative emissions. However, the LCA will be further updated following testing in operational environment to account for the source of the feedstock and any fugitive emissions that may occur.

The carbon assessment model provides a comparison of the carbon emissions associated with the EPi pure pyrolysis technology when compared against alternative waste disposal options. These include waste incineration for power generation and waste gasification for power generation.

Waste incineration assumes carbon dioxide is emitted as the SRF is combusted. Emissions are calculated from the non-biogenic carbon content of SRF, assuming complete combustion of all carbon occurs, and all carbon is emitted. This is calculated to produce 1.63 tonnes CO_2/tonne SRF.

Waste gasification converts SRF to syngas and combusts the syngas to produce electricity. Emissions are calculated from the non-biogenic carbon content of SRF, assuming a 95% conversion efficiency from SRF to syngas. It is also assumed that the non-emitted carbon char does not result in any negative emissions. Because in waste gasification, there is oxygen present, which is used to convert the feedstock to produce syngas. This oxygen facilitates combustion, and typically, any carbon that is not converted into syngas (i.e. carbon char) is assumed to be either disposed of or used in a way that does not contribute to negative emissions. Because of the combustion step, the remaining carbon char is treated as a waste or as non-emitted carbon, without contributing to long-term carbon sequestration. This is calculated to produce 1.55 tonnes CO_2/tonne SRF. Operational and transport emissions have been excluded from the boundary of all processes, and results are provided per unit of SRF. For consistency, negative emissions associated with hydrogen production have not been included here.

As shown in Figure , the EPi hydrogen production is found to have significantly less emissions released to atmosphere when compared to incineration and gasification. This is primarily due to the designed Gas Refinery system and carbon sequestered as char and carbon black.

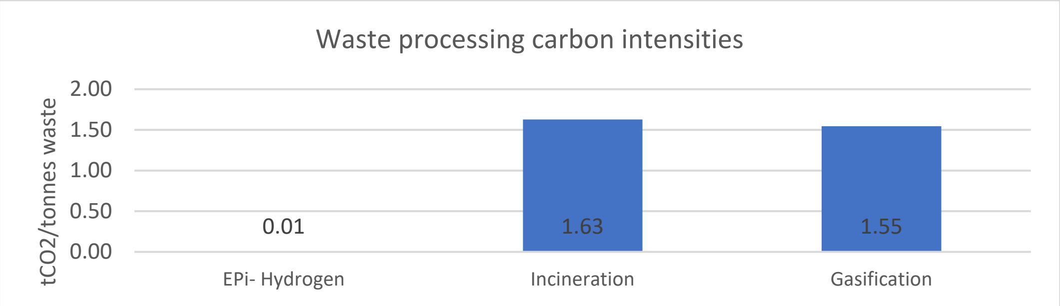


Figure 7 Carbon intensity of EPi hydrogen process compared to other waste disposal methods

LCA analysis demonstrates that process has net negative emissions of 0.805 tCO2/hr. The energy requirement of the process is 1641 kWe. Assuming the plant operates at full capacity for 7800 hours a year, the total energy consumption per year is:

$$Energy\ consumption = 1641\ kWe\ x\ 7800\ hours/year = 12{,}799{,}800\ kWh/year$$

$$Hydrogen\ production = 0.196\ tonnes/hour\ x\ 7800\ hours/year = 1{,}528.8\ tonnes\ of\ H_2/year$$

The Lower Heating Value (LHV) of hydrogen is approximately 120 MJ/kg.

120MJ/kg x 1000kg/tonne = 120,000MJ/tonne

$$Hydrogen\ product\ MJ_{LHV} = Mass\ of\ Hydrogen\ Product\ x\ Hydrogen\ Product\ LHV = 1528.8\ tonnes/year\ x\ 120{,}000\ MJ/tonne = 183{,}456{,}000\ MJ/year$$

$$Negative\ emissions\ per\ year = 0.805\ tonnes/hour\ x\ 7800\ hours/year = 6279\ tonnes\ CO_2/year\ (net\ negative\ emissions)$$

The total GHG emissions is the emissions from energy use minus the negative emissions from the process and LCA calculation already includes grid electricity. Thus,

$$Net\ GHG\ emissions = -\ 6279\ tonnes\ CO_2/year\ (net\ negative)$$

Then,

$$GHG\ Emission\ Intensity = \frac{Total\ GHG\ emissions\ (kgCO_2)}{Hydrogen\ Produced\ (MJ)}$$

$$GHG\ Emission\ Intensity = \frac{-6{,}279{,}000\ (kgCO_2/year)}{183{,}456{,}000\ (MJ/year)}$$

$$GHG\ Emission\ Intensity = -0.034\ gCO_2e/MJ$$

The GHG Emission Intensity is approximately -0.034 gCO_2e/MJ, indicating that our process is net carbon-negative and well below the 20 gCO_2e/MJ threshold set by the Low Carbon Hydrogen Standard.

3.5. Updated Commercialisation Plan

3.5.1. Social Value Work

EPi tasked the University of Suffolk, supported by Vertigo SDC Ltd, to assess social value alongside technical and commercial progress (please refer to EPi Final Social Value Report).

The social value focus covered six key areas: SME and entrepreneur engagement, apprenticeship and workforce development, site visit strategy, employment potential, future community fund, and commercialisation factors. While delays in project execution have slowed some activities, the project has built a solid base of knowledge, partnerships, and forward plans. Key social value outcomes are summarised as below.

1. SME and Stakeholder Engagement: Strong connections were built across SMEs, large industrial players, local authorities, and innovation bodies (e.g., Suffolk Chamber of Commerce, Freeport East, Hydrogen East), positioning the region for future hydrogen and carbon-based innovation.
2. Apprenticeship and Skills Pathways: Comprehensive mapping of local and national apprenticeship schemes, ensuring readiness for future recruitment, training, and placement opportunities once the demonstration site progresses.
3. Community Integration: A structured site visit strategy was developed to engage educational institutions, community groups, regulators, and businesses, helping to build public trust and awareness.
4. Community Benefit Fund: EPi committed to a voluntary fund linked to plant throughput, supporting local social and environmental projects, with Babergh and Mid Suffolk District Councils lined up as fund administrators.
5. Employment and Economic Impact: Over a ten-year rollout, the project is projected to create 2,454 jobs by 2035, spanning direct site roles, construction, supply chain, and indirect market jobs, contributing significantly to local and national economic development.

The following key figures and highlights summarise the major outcomes, targets, and insights from the Pure Pyrolysis Refined project, reflecting its expected social and environmental impact.

- **Employment Impact:** The total employment impact is projected to reach approximately 2,454 jobs by 2035. Of these, 1,272 jobs (52%) will be direct on-site roles, 110 jobs (4.5%) will be direct off-site (head office) roles, 800 jobs (33%) will come from construction and installation activities, and 272 jobs (11%) will be created indirectly within the supply chain. In terms of skill levels, about 12% of roles will be highly skilled, 69% will be skilled, and 18% will be unskilled.
- **Community Benefit Fund:** EPi has committed to a Community Benefit Fund, calculated as £1 per tonne for the first three modules, £0.50 per tonne for the next three, and £0.25 per tonne beyond that. This would result in estimated annual contributions of £24,000 for three modules, £36,000 for six modules, and £48,000 for twelve modules, providing direct funding for local social and environmental projects.
- **Environmental Contributions:** Through the production of clean hydrogen, carbon product recovery, and integration with decarbonisation initiatives, EPi's project contributes to the UK's Net Zero agenda and promotes circular economy principles by converting waste into valuable products and reducing reliance on fossil-based fuels and materials.

3.5.2. Deployment of Commercial Plant

Despite the omission of the planned trials within the framework of the current H2BECCS programme, EPi will continue with the deployment of the commercial reference plant in order to fully demonstrate the technology at scale. The funding necessary to enable this project is currently being secured, and the revised internal programme indicates that the plant will be deployed in the last quarter of 2025. EPi intends to continue the work undertaken as part of the H2BECCS programme and will invite DESNZ to visit the operation at the appropriate time. Performance data and analysis will be shared and detailed performance reports will be made available to DESNZ.

In collaboration with HiiROC, the providers of the Plasma Torch technology, a demonstration of the final phases of the process is currently being organised at the HiiROC test facility, located at the Centrica site in Brigg, North Yorkshire. This demonstration will involve the creation of a gas mixture that replicates the composition of gases produced during earlier trials, which have formed the foundation of the work conducted over the past 20 months. During the demonstration, samples of both hydrogen and carbon black will be produced. The dates for this demonstration are currently being arranged. However, to allow sufficient time for acquiring the necessary gases to create the correct compositional mix, the demonstration is being planned for the latter part of March 2025.

3.5.3. Roll-out Targets

As previously referenced in the separate report entitled *Key Commercialisation Factors* (Deliverable 8.07), EPi has outlined detailed roll-out targets for the EPi technology in the UK, as presented in Table below. This table illustrates the target number of plants to be established over the next 10 years, along with the required levels of feedstock and calculations indicating the expected volume of outputs. This programme is capable of making a significant contribution to Hydrogen BECCS value chain and the UK's carbon targets. The UK's carbon budget targets[9], as set under the Climate Change Act, are legally binding limits on the total amount of greenhouse gases the country can emit over a set period, typically five years. The carbon budgets are designed to ensure the UK meets its long-term goal of achieving net-zero greenhouse gas emissions by 2050.

- Sixth Carbon Budget (2021-2025 to 2029-2033): The target is to reduce emissions by 78% by 2035, compared to 1990 levels.
- Net-Zero by 2050: The UK aims for a 100% reduction in GHG emissions by 2050, a crucial part of meeting the global climate change goals of the Paris Agreement.

These budgets guide the UK's efforts to decarbonise various sectors, including energy, transport, and industry, with carbon capture technologies like H2BECCS playing a role in achieving these emissions reduction targets.

Table 8 Target number of plants over the next 10 years, along with levels of required feedstock and calculated outputs

Targets	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
No of Plants developed each year	1	2	4	6	6	6	6	6	8	8
Cumulative No of Plants	1	3	7	13	19	25	31	37	45	53
Annual Feedstock Requirement	50	150	350	650	850	1250	1550	1850	2250	2,650

[9] Why Net Zero - GOV.UK, Carbon Budget Delivery Plan, UK enshrines new target in law to slash emissions by 78% by 2035 - GOV.UK Carbon Budgets - GOV.UK

Targets (,000 tonnes)	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Annual Hydrogen Production (,000 tonnes)	9	27	63	117	171	225	279	333	405	477
Annual Carbon Char Production (,000 tonnes)	4.8	14.4	33.6	62.4	91.2	120.0	148.8	177.6	216.0	254.4
Annual Carbon Black Production (,000 tonnes)	26.3	78.8	184.0	341.6	499.3	657.0	814.7	972.4	1182.6	1392.8
Net Carbon Removal (,000 tonnes)	27.4	82.2	191.9	356.3	520.8	685.4	849.9	1014.4	1233.6	1452.9
Cumulative Net Carbon Removal (,000 tonnes)	27.4	109.6	301.6	657.9	1178.8	1864.1	2714.0	3728.3	4962.0	6414.9

The figures are calculated on the following amounts per module per annum.

- Feedstock 8,000 tonnes
- Hydrogen 1,510 tonnes
- Carbon char 800 tonnes
- Carbon black 4,380 tonnes

All previous iterations of the EPi core technology have been produced and operated at full commercial scale, with each module designed for a nominal throughput of 1 tonne/hr, ensuring full operational capability. The reactors used in the PIMOT test facility for the newly designed Gas Refining Unit were built at full operational scale, so no scaling up of the technology itself is needed for commercial operation. Scaling up involves adding more modules to meet plant output, rather than increasing the size of individual units like the pyrolyser or plasma torch. This modular expansion ensures the same efficiency, durability, and reliability, as the individual modules are already proven at full scale. Maintenance is streamlined since each module operates autonomously, and additional modules can be integrated without major changes to the design or complexity.

3.5.4. Commercial Opportunities

The key targets for feedstock in the early stages of the commercial roll-out will be residual waste from the Commercial and Industrial (C&I) waste sectors. These waste streams will be predominantly provided through the independent waste operators.

As the programme gains a stronger foothold in the marketplace and more plants become operational, it is expected that there will be greater recognition of the technology's environmental credentials. The ability to meet the requirements of Best

Available Technology (BAT), while fully embracing the principles of proximity for waste treatment within the communities where it is generated, ensures that the EPi technology meets various environmental targets while providing a commercially viable solution for waste treatment. As the environmental and commercial benefits of the EPi technology become more widely recognised, increasing interest from major established waste companies and local authorities.

The key markets for early deployment of hydrogen fuels have been identified as heavy industry and the road and marine transport sectors. EPi has taken steps to engage early with both sectors (details below). While there has been innovation in hydrogen storage and transportation, EPi has determined that co-location at the point of demand is the preferred option. This eliminates transportation costs and logistics, minimising storage needs by matching production to demand with a small buffer reserve on-site. The Pure Pyrolysis Refined technology offers multiple income sources, including hydrogen sales, gate fees from residual waste, carbon char, carbon black, and carbon credits. The ability to use various feedstocks, such as mixed wastes and sustainable biomass, adds flexibility and supports a circular economy.

EPi describes its operations as Advanced Conversion and Recovery facilities, which significantly aids in planning and has generally earned broader acceptance within the local communities. The detailed report titled 'Key Commercialisation Factors[10]' did not identify any insurmountable barriers to the planned deployment programme. However, it did identify potential challenges in establishing commercial outlets for the carbon char and carbon black. The planned roll-out of the EPi technology will produce significant quantities of solid carbon in the form of carbon char and carbon black.

While there are established and emerging markets for various carbon products, these markets need to be developed to fully realise their benefits in the UK. Carbon char, a lower-value product, is ideal for use in construction materials and road substrates. It has been shown to improve strength and durability whilst qualifying as sequestration. Derived from biomass or organic material, carbon char can also enhance soil quality, replacing lost hydrocarbons caused by over-farming and overuse of chemical fertilisers. The char can carry nutrients and improve water retention. These benefits are well-documented, with long-term sequestration contributions. Opportunities for carbon black are equally varied, although many of these applications may not currently qualify under existing carbon sequestration guidelines. Depending on the grade, carbon black, can be used in production of advanced electronics, particularly components for super-computers and high-performance lithium batteries, as these applications benefit from carbon black's elevated electrical conductivity.

One of EPi's key technology partners has recently completed trials on their 4th generation unit, producing graphene from carbon char and carbon black. Both carbon black and graphene are finding a range of new applications as a liquid media for 3D printers. These materials enhance the strength, durability, and colour fastness of components produced in this way. It is entirely feasible that, in the near future, these

[10] EPi Key Commercialisation Factors Final, D8.07

applications may also qualify under the carbon sequestration standards. In the interim, EPi will determine the most advantageous uses for the carbon outputs.

Many sectors of industry could benefit significantly in their journey to Net Zero by utilising the opportunities provided by the various forms of carbon from the EPi process. These commercial opportunities span across industries including the rubber industry, printing and various construction materials. As the production of carbon increases through emerging technologies, it is likely to serve as a catalyst for a reduction in market prices. This reduction in cost will open up new markets, thereby expanding the opportunities for these highly specialised forms of carbon for high-tech applications, including batteries, surface coatings, composites and electronics.

The following key figures and highlights summarise the major outcomes, targets, and insights from the Pure Pyrolysis Refined project, reflecting its commercial ambitions.

- **Deployment Plans:** EPi's deployment targets between 2026 and 2035 include a total of 53 cumulative plants, designed to process 2.65 million tonnes of feedstock per year and produce 477,000 tonnes of hydrogen annually. This equates to less than 3.6% of the UK's annual waste arisings from just two sectors (Household and Commercial & Industrial waste). The cumulative development programme including the projected increase in feedstock demand over this period is summarised in Table .
- **Market Positioning:** The UK Government is committed to delivering a world-class hydrogen sector as part of its Clean Energy Superpower and Growth Missions, for example through the strategic investment of £500 million to develop the first regional hydrogen transport and storage network as part of its wider commitment to scaling up low-carbon hydrogen infrastructure[11]. EPi's ten-year rollout aligns with these ambitions and is positioned to make a meaningful contribution to the UK's net-zero transition.
- **Carbon Products:** In the carbon markets, the assumed price for carbon char is £65 per tonne, while the average accepted sales price for carbon black, after accounting for refining and transport costs, is £630 per tonne. Specialty carbon black products can command much higher prices, reaching up to £7,000 per tonne in niche markets such as battery materials and conductive additives.
- **Strategic Partnerships:** Key infrastructure collaborations include Freeport East's 500 MW Green Hydrogen Hub, expected to deliver £5.5 billion in Gross Value Added and create around 13,500 new jobs over the next decade. Additionally, the Sizewell C hydrogen bus pilot project may scale up to one of the world's largest hydrogen bus fleets, driving local hydrogen demand. The Tees Valley hydrogen hub also received a £7 million government investment to decarbonise logistics and support hundreds of UK jobs.
- **Project Pipeline:** EPi is advancing significant national and international opportunities, including a 12-module site in Theale (West Berkshire) with planning expected in March 2025, a 100,000 tonnes/year project in the Cardiff

[11]Department of Energy Security & Net Zero, Hydrogen update to the market, July 2025, pg 6, https://assets.publishing.service.gov.uk/media/6880b2139fab8e2e86160efe/hydrogen-update-to-the-market-2025.pdf

Region, a coal site remediation initiative in South Wales, and an advanced-stage partnership with the Maldivian government to provide sustainable waste and energy management solutions.

3.5.5. EPi Technology and Regulatory Engagement

As previously noted, the unprecedented nature of the process, which has resulted in complexities in securing planning permits, has contributed to delays in the current project's timelines. Recent discussions with senior technical personnel at the EA have been highly constructive, while achieving "Type Approval" for EPi technology in the short term may not be feasible, there is a tangible possibility that developments incorporating identical operational plants, where the key components of the EPi technology can be replicated in a standardised format, may eventually qualify for such approval.

The specialist technical personnel at the EA have confirmed that the EPi process modifies the output gas to such an extent that the end product is likely to meet the criteria for "End of Waste" status. They are not aware of any other technology in the waste sector that has adopted a similar approach. These indications have emerged from high-level engagement with the EA. Achieving this status would streamline EPi's planning and permitting process. Combined with the technology's small footprint, low profile, zero airborne emissions, carbon capture, and net-negative carbon operations, future planning applications are expected to progress more efficiently. Notably, EPi has historically secured nine consented planning applications for 1 tonne/hr commercial-scale modules, all processed and approved within 13 weeks or less prior to Covid.

3.5.6. Current Projects

Over the past two years, EPi have been developing a number of commercial opportunities for the near-term deployment of the EPi technology. There is significant interest from various parties, however, for the purpose of this update, focus has been placed on those projects that have made real progress toward deployment. In each case, the key metrics for determining commercial viability include projects that have secured a site lease, obtained outline or planning permission in principle for activities aligned with the intended operations, identified reliable sources of feedstock that can be contracted to the project, and confirmed outlets for the process outputs

Major UK Hydrogen Transport Hub

Major UK Hydrogen Refuelling Facilities - Various Locations

Various locations across South Wales

Theale, West Berkshire: EPi holds a formal option on a site in Theale, Near Reading. An application for a 12-module EPi operation previously submitted to the West Berkshire Council was the subject of a planning committee meeting convened on the evening of the 5th of March 2025, the application was unanimously approved by the councillors, officers and planning committee members, who offered strong words of support and expressed their gratitude to EPi for the opportunity brought to the West Berkshire area. Formal planning consent was issued on the 18th March 2025.

This 2-hectare site, in Theale, is part of an operational waste-designated area, partially occupied by Hadleys, a local waste management company. Hadleys' will provide feedstock from their existing operations to the EPi plant. Additionally, further feedstock is available from other waste operators in the immediate vicinity

This arrangement benefits the existing operation by eliminating the need to transport residual waste from Hadleys' off-site. Key output uses are being established through two main channels. Ryze have been Invited to explore the opportunity of establishing a hydrogen refuelling facility at the nearby M4 Motorway Service Station, less than a mile from the EPi site at Theale. Additionally, EPi has been collaborating with a third-party technology provider on an advanced chemical conversion process using hydrogen and carbon monoxide to produce sustainable liquid fuels. This technology is nearing commercial readiness, and by the time the Theale site is operational, EPi plans to divert some hydrogen for renewable fuel production, including sustainable aviation fuels, with full operation expected by Q4 2026.Over the past two years, EPi's development network has established a client base for liquid fuels and/or Bio-Naphtha, which includes major international corporations, along with several European airlines

Wider Commercial Opportunities:
EPi is currently pursuing a number of wider opportunities for export markets, with projects currently under consideration in Norway, Denmark, Romania, North America and Senegal.

3.6. Key Successes

The "Pure Pyrolysis Refined" project fully aligns with the goals of the H2BECCS Innovation Programme by delivering a net-zero hydrogen production process from a feedstock with biogenic content, while enabling carbon capture and storage. This innovative system converts biomass and waste into clean energy, producing high-quality hydrogen, and solid carbon residues, while achieving negative carbon dioxide emissions.

Key benefits of this technology include:

1. **No combustion and emissions-free:** Utilising electricity as its parasitic load, the process ensures zero airborne emissions at all stages.
2. **Three-stage carbon capture:** Carbon is captured as solid residue from pyrolysis and PT processes and converted into hydrogen from CO_2/CO containing gas.
3. **Landfill reduction:** The process significantly decreases waste directed to landfills by processing a wide range of feedstocks, mitigating leachates and harmful runoff.
4. **Modular, location-flexible design:** The scalable plants can be deployed locally, aligning with waste generation points while achieving hydrogen production targets and contributing to the UK's sixth carbon budget.

Over a five-year plan, 50 plants across the UK will treat approximately 85,000 tonnes of waste per plant annually, collectively producing over 440,000 tonnes of pure hydrogen each year. The modular design ensures local adaptability, driving a shift towards a circular economy while tackling environmental challenges, including greenhouse gas emissions and waste management inefficiencies.

The installation of the first phase of six modules at Theale, Near Reading will demonstrate the project's scalability, with an annual production target of 9,600 tonnes of hydrogen. This groundbreaking technology positions itself as a viable and sustainable solution to waste and energy challenges, contributing to atmospheric carbon drawdown and advancing the hydrogen economy. Other environmental benefits of this project can be presented as:

1. **Reduction in greenhouse gas emissions:** The project significantly reduces CO_2 emissions through effective carbon capture and utilisation processes. Gas refinery system is designed to minimise CO_2 by-products, achieving zero direct emissions from the plant.
2. **Waste-to-energy conversion:** Conversion of waste materials into valuable products, such as hydrogen, carbon black, and char, promotes sustainable waste management and reduces landfill dependency.
3. **Land use optimisation:** The plant leverages an existing industrial site, minimising land disturbance and avoiding the need for large-scale land acquisitions. Pyrolysis and downstream technologies require compact facilities, reducing the overall land footprint.
4. **Water conservation:** Integrated process water circuit system minimises freshwater usage, recycling water within the process for cooling and reaction purposes (as a steam input to catalytic reactor 1). Any discharged water is treated to meet environmental safety standards.
5. **Air quality improvements:** Harmful emissions such as methane, CO, and particulate matter is reduced through advanced reactor designs modelled and pollution control technologies (such as bag filters). Carbon black and carbon char production provides a sustainable alternative to conventional methods, reducing associated air pollution.
6. **Soil protection:** The project avoids any direct soil contamination by implementing stringent waste handling protocols and ensuring that char and other by-products are either safely disposed of or reused in eco-friendly applications.
7. **Energy efficiency:** Heat recovery study enabled the reuse of waste heat within the plant, significantly reducing the need for external energy inputs. Achieving 67% heat recovery demonstrates excellent energy integration and supports sustainability goals.
8. **Circular economy promotion:** By producing hydrogen and carbon black as value-added products, the project contributes to a circular economy, creating economic and environmental benefits.
9. **Trade-off considerations:** While the project offers significant environmental benefits, trade-offs such as energy consumption during start-up phases and potential impacts of transportation logistics for feedstock and products have been

carefully assessed. Comprehensive mitigation strategies, such as optimising logistics and using renewable energy for auxiliary power, ensure that negative impacts are minimised.

10. **LCOH:** Finally, as demonstrated in the sections above, the LCOH can change between 1.6 £/kg and 3.3 £/kg. When compared against the underwritten cost offered under the terms of the recent HAR of £9.49 per kg, provides tangible evidence to demonstrate how competitive the EPi technology offering can be.

3.7. Persistent Barriers

Addressing persistent barriers is a critical component of ensuring the sustainability and viability of any large-scale project. These barriers often encompass complex trade-offs and broader environmental impacts across key areas such as air quality, soil health, water resources, and land use.

While the Pure Pyrolysis Refined project aims to deliver significant environmental and economic benefits, it is crucial to manage potential risks to ensure regulatory compliance and alignment with sustainability goals. Through a comprehensive risk register, treatment plan, and mitigation strategies, the project proactively addresses challenges to minimise adverse impacts and maximise positive outcomes, as outlined in section 3.6. However, persistent barriers require ongoing monitoring and improvement for long-term success, demonstrating the project's commitment to responsible resource management, stakeholder engagement, and environmental stewardship. (See previously submitted Environmental Product Declaration (EPD), RAMs, and O&M documents)

1. **Air Quality:** Transportation of feedstock and products, as well as auxiliary power which may be needed during start-up phases. These may contribute to localised air pollution such as particulate matter from feedstock, minor methane, NOx, CO_2 and CO emissions from vehicles using natural gas, diesel or fossil fuels. Diesel generators or other fossil fuel-based systems used during start-up phases whilst awaiting connection to the grid, can emit NOx. To mitigate these, some of the energy needed for auxiliary power (cooling water system, silicone oil circulation etc.) will be provided by the surplus energy produced by the process, as a renewable energy resource. To further reduce emissions during transportation phases, logistic optimisation plans will be implemented.
2. **Soil:** Improper handling of char or other solid residues could result in soil contamination. Stringent waste management protocols ensure safe handling of by-products like char, carbon black.
3. **Water:** Water consumption and potential discharge of untreated wastewater may impact local water bodies. To mitigate this risk, there is a closed-loop water recovery system which minimises freshwater demand. Additionally, monitoring and auditing protocols are in place to comply with water management regulations. In the event that any wastewater is generated, this will be collected in purpose-built tanks and sent to local waste treatment facilities.
4. **Land use:** The Pure Pyrolysis Refined project prioritises the use of existing industrial sites to minimise land disturbance. Compact and modular plant design

reduce the overall land footprint. Environmental Impact Assessments (EIAs) informed the process of site selection and land-use planning.

The project adheres to international and national environmental standards for environmental management and industry-specific regulations for emissions, water, and waste management. A dedicated HSE (Health, Safety, and Environment) team ensures that all operational activities align with regulatory requirements, and any identified risks are promptly addressed through the treatment plan. Regular communication with local authorities, regulatory bodies, and community stakeholders ensures transparency and addresses any emerging environmental concerns. Feedback from stakeholders is integrated into the risk register to continuously refine mitigation strategies.

3.8. Lessons Learned and Next Steps

While the Pure Pyrolysis Refined project has made significant progress, several key lessons have emerged that will shape the next steps.

Environmental licence delay: One of the major challenges encountered was the extended timeline for obtaining the necessary Environmental Licence, which delayed the commencement of testing and operations. This issue highlighted the need for more proactive engagement with regulatory bodies earlier in the process, as well as closer monitoring of permit approval timelines. As another solution, using a site with an existing environmental licence could be considered to bypass the licensing delay and enable site work to commence more quickly. However, this may be limited in practice due to the novel nature of the technology and the need for site-specific permitting. Since although the technology is novel, the activities are generally aligned with similar industrial or waste-processing operations. Leveraging pre-existing site permissions where the purpose is comparable could help bypass some licensing delays and enable site work to commence more quickly, helping to keep the project on track.

Investor securing challenges: Additionally, the difficulty in securing an investor led to delays in initiating the site work. Moving forward, it will be crucial to intensify efforts in identifying and securing reliable funding sources to ensure the timely mobilisation of resources for field operations. This also underscores the importance of having contingency plans in place to address financial uncertainties. The completion of a commercial reference plant is considered a necessity to ensure that investment funds will be made available for ongoing development and technology deployment.

The project team has identified several key adjustments to its approach to risk management and project management as a result of the lessons learned. The challenges encountered, particularly with environmental license delays and securing investment, have highlighted the need for a more proactive and flexible approach.

Risk Management: The team will place greater emphasis on early engagement with regulatory bodies and closer monitoring of permit approval timelines to avoid unexpected delays. Additionally, more robust financial contingency plans will be developed to address uncertainties around securing funding.

Project Management: The team will prioritise improved time management, focusing on de-risking key project milestones, including exploring alternative sites with existing environmental licenses to avoid delays. Efforts to secure reliable funding will also be intensified for timely resource mobilisation.

These changes reflect the project's evolving approach to mitigating risk and ensuring more effective management of resources, timelines, and stakeholder engagement moving forward.

APPENDICES

APPENDIX 1

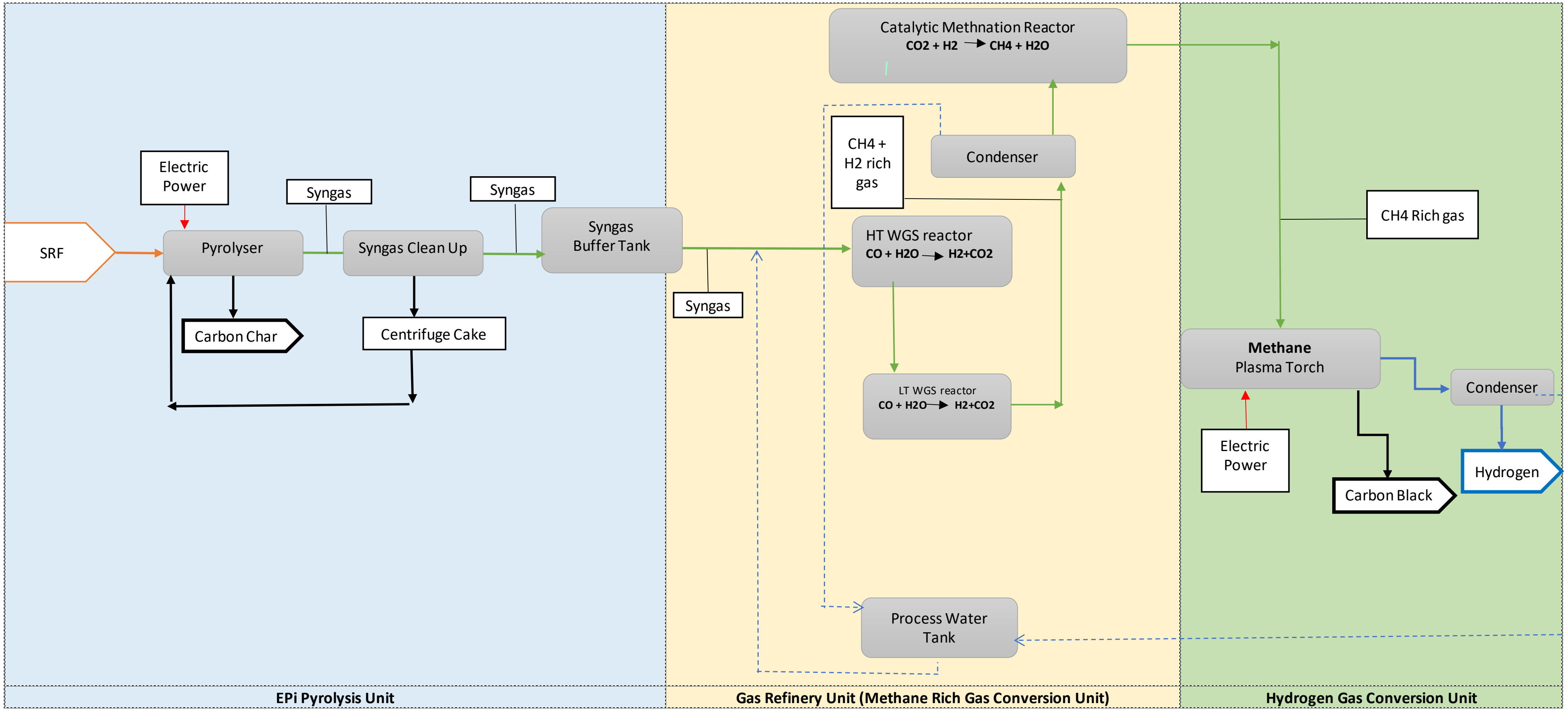


Figure A1 1 Graphical overview of the Pure Pyrolysis Refined process

APPENDIX 2

PROJECT OVERVIEW

Table A2 1 The original and final milestone plan during phase 2

	Original Milestone	Final Milestone
Q2 2023	Plant design review 1, site lease approval, social value programme,	Plant design review 1 and site lease approval.
Q3 2023	Plant design review 2, procurement & manufacture stages 1 and 2, preparation of technical specifications for gas refinery system, preparation of Factory Acceptance Test (FATs) documents and preparation of social value programme and list of target SME's and entrepreneurs.	Plant design review 2, procurement & manufacture stages 1 and 2, preparation of technical specifications for gas refinery system, preparation of Factory Acceptance Test (FATs) documents and preparation of social value programme and list of target SME's and entrepreneurs.
Q4 2023	Stage gate review-1, plant design finalisation, design optimisation - energy recovery, procurement & manufacture stages 3, 4, 5 and 6, HAZOP, planning permit / environmental licensing, site building design, documentation preparation for cold and hot commissioning, technical specifications for all parts and equipment, preparation of FAT documents and options report on apprenticeships and placements.	Stage gate review-1, plant design finalisation, design optimisation - energy recovery, procurement & manufacture stages 3 and 4, documentation preparation for cold and hot commissioning, technical specifications for all parts and equipment, preparation of FAT documents and options report on apprenticeships and placements.
Q1 2024	Stage gate review – 2, procurement & manufacture stage 7 and 8, site visit strategy, preparation of O&M Manual, SOPs and protocols for all activities during day-to-day operations, review and finalisation of testing plan - functional, performance and reliability tests, preparation of impact assessment checklist	Experimental validation of reactors, submission and award of planning permit, completion of site building design, documentation preparation for process optimisation & stabilisation, report on strategy for site visits during the operational phase.
Q2 2024	Procurement & manufacture stages 9 and 10, mechanical and electrical installation stages 1, cold commissioning, report on employment potential.	Updating Bill of Material (BOM), site layout, process flow diagrams (PFDs), piping and instrumentation diagrams (PI&Ds), preparation of technical specifications for catalysts and consumables, procurement & manufacture stages 5 and 6, preparation of future community fund report

	Original Milestone	Final Milestone
Q3 2024	Stage gate review-3, mechanical and electrical installation stages 2, hot commissioning, UKCA/CE certification & testing review, process optimisation & stabilisation stage 1, future community fund report, commercialisation report.	Stage gate review – 2, procurement & manufacture stage 7, preparation of report on employment potential.
Q4 2024	Draft final report, process optimisation & stabilisation stage 2, Functional & Performance and Reliability Testing, process scale up, carbon life cycle assessment, social values outcome report.	HAZOP (Hazard and Operability) study, procurement & manufacture stage 8, proof of manufacturing progress, FATs results, declarations of conformity, evidence of submission of Environmental License pack, preparation of commercialisation report.
Q1 2025	Final report, project closure.	Procurement & manufacture stages 9 and 10, social values outcome report and submission of final report.
Q2-Q4 2025		Award of Environmental License , mechanical and electrical installation, cold and hot commissioning, process optimisation and stabilisation, Functional & Performance and Reliability Testing, process scale up, carbon life cycle assessment.

Table A2 2 Estimated and realised cost break down for the designed system under H2BECCS Project

	Estimated Cost	Realised Cost
CAPEX - H2BECCS Project Scope	**1 Module**	**1 Module**
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]

	Estimated Cost	Realised Cost
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
Total	£2,518,650	£2,741,346

APPENDIX 3-1
ENGINEERING DESIGN

DRAWINGS

[REDACTED CONTENT]

Figure A3-1 1 Flowchart of Pyrolysis Pilot Plant at Imperial Collage

[REDACTED CONTENT]

Figure A3-1 2 Gas connection

[REDACTED CONTENT]

Figure A3-1 3 Design drawing of pilot-scale validation reactor-1

[REDACTED CONTENT]

Figure A3-1 4 Design drawing of pilot-scale validation reactor-2

PIMOT LABORATORIES – VALIDATION TESTS

Figure A3-1 5 Filling pump buffer with silicon oil

Figure A3-1 6 Gas panel, water condenser

Figure A3-1 7 Temperature control box

Figure A3-1 8 Oil cooling system

Figure A3-1 9 Cooling oil loop

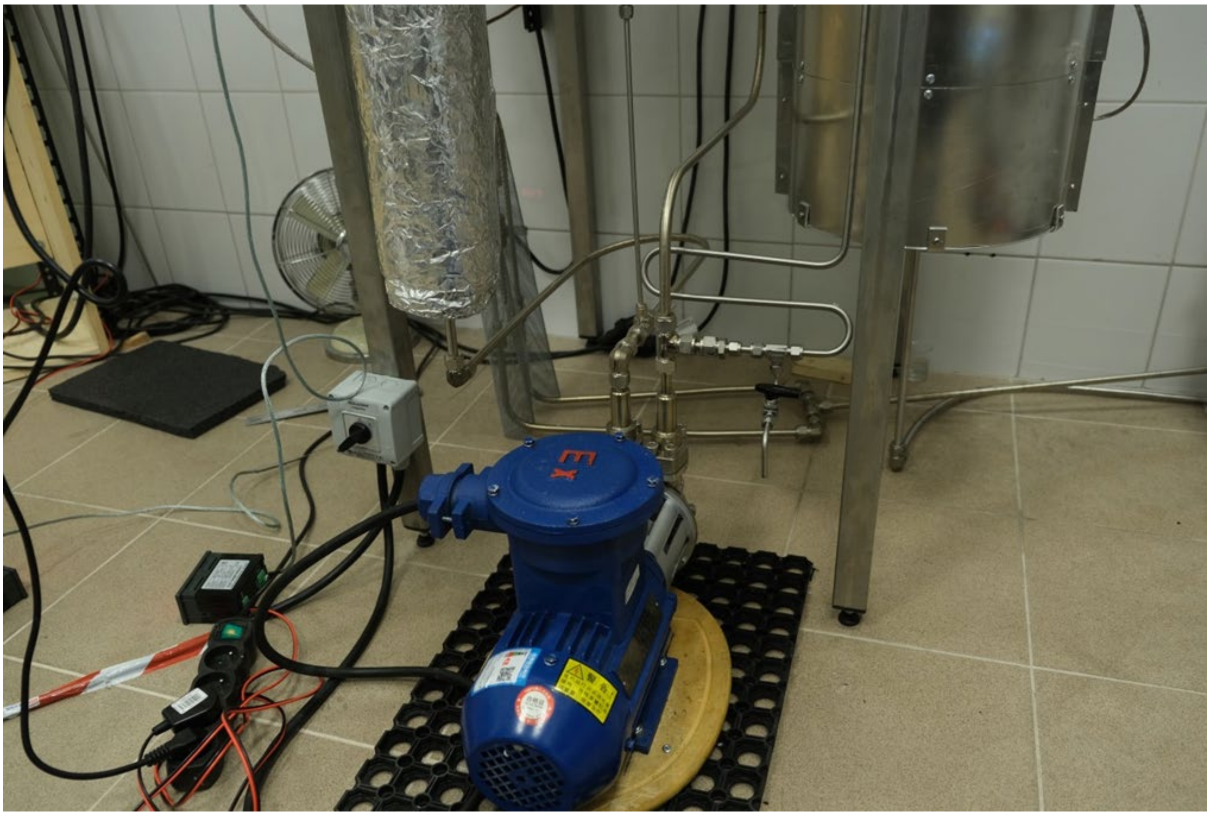


Figure A3-1 10 Oil pump

Figure A3-1 11 CO2 evaporator thermostat

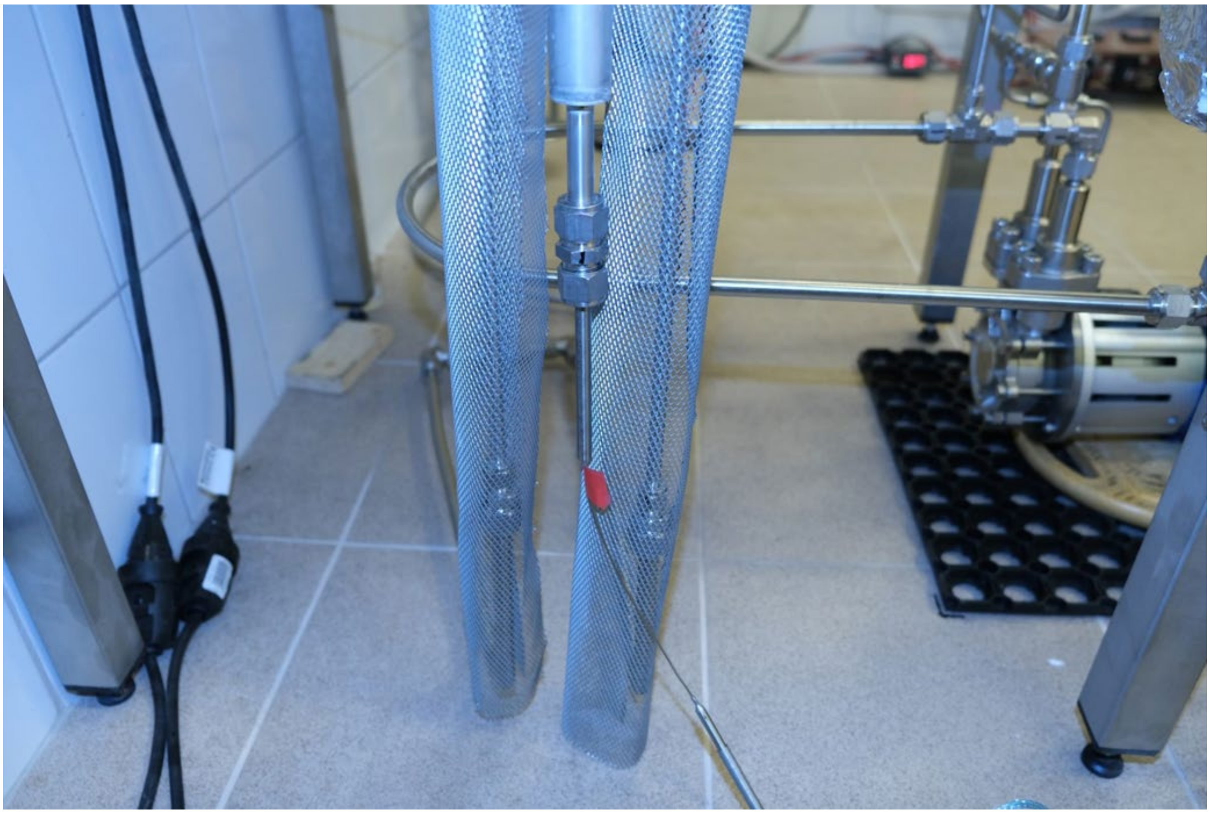


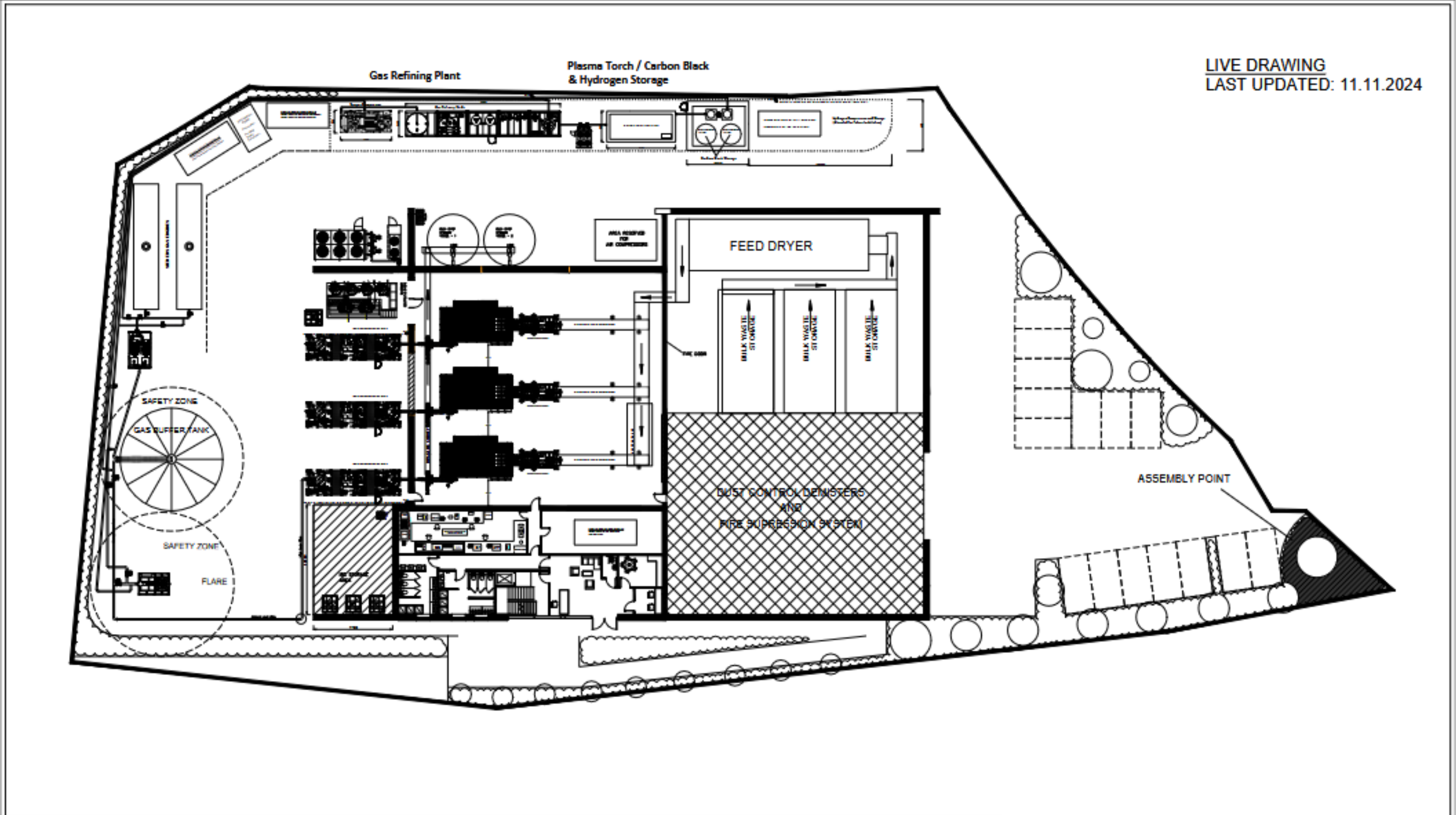
Figure A3-1 12 End of 2m long thermowell with sliding thermocouple

Figure A3-1 13 Hydrogen and CO2 flowrates

Figure A3-1 14 Pressure in medium pressure experiment

Figure A3-1 15 Collecting water product, in average 1200-1300 g from 20 min.

FINAL DESIGN DRAWINGS – SITE LAYOUT, PFDs, P&IDSs



SITE SUMMARY

Overall Area (Excl. Parking and Access)	≈4500 m^2	Bulk Storage of Feedstock	3 x 36 = 108 tonne
Internal Footprint (Incl. Canopy)	≈2400 m2	Assumed Feedstock Density	150 kg/m3
External Footprint	≈2100 m2	Feedstock Storage Capacity	≈1.5 days
Dryer Output Capacity	1000 kg/hr	Gas Storage (NPT)	480 m3
Moisture Reduction Range	25% to 5%	Gas Standby Provision	38.4 mins (1 Module)

Figure A3-1 16 Site layout

[REDACTED CONTENT]

Figure A3-1 17 P&ID - Gas Refinery Unit Reactors

[REDACTED CONTENT]

Figure A3-1 18 P&ID - Compressor & Pumps & PT

[REDACTED CONTENT]

Figure A3-1 19 PFD - Gas Refinery Skid 1

[REDACTED CONTENT]

Figure A3-1 20 PFD - Gas Refinery Skid 2

[REDACTED CONTENT]

Figure A3-1 21 PFD - Gas Refinery Skid 3

[REDACTED CONTENT]

Figure A3-1 22 PFD - Hydrogen Conversion

[REDACTED CONTENT]

Figure A3-1 23 PFD - Syngas Compressor Skid

HIGH FIDELITY MODELLING RESULTS

Table A3-1 1 Inlet and output gas composition and conditions

	Reactor 1 Inlet		Reactor 1 Outlet		Rector 2 Inlet		Reactor 2 Outlet	
T (C)	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-
p (abs bar)	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-
F (kg/s)	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-
h (kJ/kg)	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-
F (kmol/h)	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-
-	w (wt%)	x (mol%)	w (wt%)	x (mol%)	w (wt%)	x (mol%)	w (wt%)	x (mol%)
H_2	5.6%	39.2%	5.8%	41.0%	5.8%	41.0%	6.0%	42.3%
CO	**6.8%**	**3.4%**	**3.2%**	**1.6%**	**3.2%**	**1.6%**	**0.7%**	**0.4%**
CO_2	**3.4%**	**1.1%**	**9.0%**	**2.9%**	**9.0%**	**2.9%**	**12.9%**	**4.2%**
N_2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CH_4	35.8%	31.7%	35.8%	31.7%	35.8%	31.7%	35.8%	31.7%
C_2H_6	31.4%	14.8%	31.4%	14.8%	31.4%	14.8%	31.4%	14.8%
C_3H_8	4.3%	1.4%	4.3%	1.4%	4.3%	1.4%	4.3%	1.4%
C_4H_{10}	1.3%	0.3%	1.3%	0.3%	1.3%	0.3%	1.3%	0.3%
C_5H_{12}	1.1%	0.2%	1.1%	0.2%	1.1%	0.2%	1.1%	0.2%
C_2H_4	0.5%	0.3%	0.5%	0.3%	0.5%	0.3%	0.5%	0.3%
C_3H_6	0.5%	0.2%	0.5%	0.2%	0.5%	0.2%	0.5%	0.2%
Water	9.2%	7.3%	6.9%	5.5%	6.9%	5.5%	5.3%	4.2%

Table A3-1 2 Gas composition change

To	Reactor 3 Inlet		Rector 3 Outlet	
T (C)	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-
p (abs bar)	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-
F (kg/s)	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-
h (kJ/kg)	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-
F (kmol/h)	[REDACTED CONTENT]	-	[REDACTED CONTENT]	-
	w (wt%)	x (mol%)	w (wt%)	x (mol%)
H_2	**6.3%**	**43.9%**	**3.7%**	**28.2%**
CO	**0.8%**	**0.4%**	**0.1%**	**0.0%**
CO_2	**13.6%**	**4.3%**	**0.0%**	**0.0%**
N_2	0.0%	0.0%	0.0%	0.0%
CH_4	**37.6%**	**33.0%**	**42.9%**	**41.5%**
C_2H_6	33.0%	15.4%	33.0%	17.0%
C_3H_8	4.5%	1.4%	4.5%	1.6%
C_4H_{10}	1.4%	0.3%	1.4%	0.4%
C_5H_{12}	1.2%	0.2%	1.2%	0.3%
C_2H_4	0.6%	0.3%	0.6%	0.3%

To	Reactor 3 Inlet		Rector 3 Outlet	
C_3H_6	0.5%	0.2%	0.5%	0.2%
Water	0.6%	0.5%	12.1%	10.4%

Table A3-1 3 Gas composition before and after Plasma Torch

	PT Inlet		PT Outlet	
T (C)	244.00	-	250.00	-
p (abs bar)	10.00	-	7.00	-
F (kg/s)	0.21	-	0.05	-
h (kJ/kg)	-2979.15	-	2848.71	-
F (kmol/h)	48.63	-	93.93	-
	w (wt%)	**x (mol%)**	**w (wt%)**	**x (mol%)**
H_2	4.1%	31.4%	**97.4%**	**99.7%**
CO	0.1%	0.0%	0.0%	0.0%
CO_2	0.0%	0.0%	0.0%	0.0%
N_2	0.0%	0.0%	0.1%	0.0%
CH_4	**48.5%**	**46.1%**	0.0%	0.0%
C_2H_6	37.3%	18.9%	0.0%	0.0%
C_3H_8	5.1%	1.8%	0.0%	0.0%
C_4H_{10}	1.6%	0.4%	0.0%	0.0%
C_5H_{12}	1.3%	0.3%	0.0%	0.0%
C_2H_4	0.7%	0.4%	0.0%	0.0%
C_3H_6	0.6%	0.2%	0.0%	0.0%
Water	0.6%	0.5%	2.5%	0.3%

APPENDIX 3-2
UPDATED COST ESTIMATES

Table A3-2 1 Inputs to LCOH Model

#	Input Description
1	The technical performance of the plant was based on the energy and mass balances developed by EPi in collaboration with Imperial College and SPSE. These models are based on a 6-module plant processing 6 t/h waste stream that is a mixture of SRF and waste plastics (HDPE) with 38% biogenic content by CV.
2	CAPEX covers the pre-process plant, pyrolyser, syngas treatment & char unit, Gas Refinery processes, balance of plant, CH_4 Plasma Torch as well as the project completion and handover.
3	OPEX is analysed under two main headings: fixed and variable costs. Fixed OPEX includes labour, operational overheads, and O&M costs. Additionally, as per the lease agreement put in place with the plasma torch providers, fixed operating costs also cover the lease fee and the O&M fees for the plasma torches. The variable OPEX includes the parasitic electricity costs for the overall integrated system and the consumables. Variable costs also cover the royalty fee which is paid to the PT providers for every 1kg of hydrogen produced. Finally, the revenues are demonstrated in the variable costs. Unlike other systems, EPi system has revenues; carbon black and carbon char produced in this configuration are commercial products and their disposal route is through sales. Similarly, raw materials do not incur costs, rather waste as feedstock leads to gate fees. Therefore, variable costs take into account revenues as negative streams.
4	The industrial retail price central case scenario reported by Green Book, BEIS (2021) is used as the reference for the electricity price. The average price of electricity for the next 5 years is considered as 56.8 £/MWh[12].
5	Cost estimates do not reflect cost reductions which could be achieved through global technology learning and economies of scale as the cost analysis takes into account a single six module plant. The reductions in CAPEX in the additional five modules are only observed because some of the subsystems such as software and liquid filtration units can support three modules. Therefore, costs of these equipment are accounted for twice rather than six times for each module.
6	The feedstock to be utilised is determined as a mixture of SRF from C&D waste and waste HDPE. Initial discussions with the producers indicate that the price of this raw material will amount to £85 per tonne[13] (Please refer to 3.5. Updated Commercialisation Plan).
7	The revenues from carbon black and carbon char are assumed as £630 and £65 per tonne respectively based on the preliminary discussions with the buyers (Please refer to 3.5. Updated Commercialisation Plan). The carbon char is based on the assumption that the price that construction material producers will be prepared to pay will depend upon three factors; the cost of replaced material (basic construction aggregates cost £30-40 per tonne), the value of performance benefits, and any monetary benefits from carbon reduction/sequestration (£30-40 per tonne). As such the price of carbon char is assumed as 65 £/tonne[14]. The carbon black price was determined based on the information provided by University of Suffolk. The current price trend for Carbon Black as rated by ChemAnalyst for the quarter June 2024 was €1424/MT (USD 1530/MT). Currently, in the UK market, high volume grades trade at around £1,400 per tonne, whilst speciality grades can reach up to £7,000 per tonne. However when costs for refining and transport and other potential reductions are allowed, 630 £/tonne is accepted as a reasonable sales price for the modelling exercise[15].
8	Net amount of CO_2 sequestered is calculated as the difference between the total CO_2 emitted and total CO_2 sequestered. Net CO_2 sequestered amounts to 2,161 kg/hr and 12,964 kg/hr for single and 6 module plant. Please note that this report does not account for CO_2 Transport and Storage (T&S) fees as the carbon is sequestered in the by-products and taken off-site via the buyers rather than using the CO_2 T&S network.

12 DESNZ(2025), Levelised Cost of Hydrogen Workbook V2, Tab References
13 University of Suffolk, (Nov 2024), "Key Commercialisation Factors", p: 7
14 Ibid., p:25
15Ibid., pp: 28-29

#	Input Description
9	This model assumes that the carbon prices faced over 5-year period are the Traded carbon values for modelling purposes, £/tCO2e (real 2024) as set out in Table 1 of DESNZ's 2024 Modelling Traded Carbon Values[16] The sensitivity of LCOH to carbon values is also demonstrated by running the same LCOH model on carbon prices cited in "Market Traded Carbon Values" and "Net Zero Strategy Aligned" scenarios.

Table A3-2 2 CAPEX of the integrated system

Name of the Subsystem	Cost per 1 module excl. VAT (£)	Cost per 5 modules excl. VAT (£)	Cost per 6 Modules excl. VAT (£)
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]

16 DESNZ (17 Dec 2024), "Traded Carbon Values used for Modelling Purposes", Table 1, Traded carbon values used for modelling purposes, 2024 - GOV.UK

Table A3-2 3 Total Operating Expenditures of the Integrated System for 6 Modules of Full Size Plant

Fixed Operating Costs			
Labour	**Unit**	**Salary (£/yr)**	**Total Cost (£/yr)**
Shift Leaders	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
Shift Operators	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
Maintenance	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
Total Labour Costs	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
-	-	-	-
Additional Fixed Operating Costs	-	-	-
Description	**Unit**	**Cost (£)**	**Total Cost (£/yr)**
Annual Support Fee / Telemetry	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
Annual Maintenance Costs	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
Annual Rent / Rates / Insurance	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
General Operating Overhead	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
CH_4 Plasma Torch Rental Fee	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
CH_4 Plasma Torch O&M cost	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
Total additional fixed operating costs	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
Total Fixed OPEX	-	-	[REDACTED CONTENT]
-	-	-	-
Variable Operating Costs	-	-	-
-	**Unit**	**Estimated Cost (£)**	**Total Cost (£)**
Electricity Costs - Integrated design	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
-	-	-	-
Additional Variable Operating Costs	-	-	-
Description	**Unit**	**Cost (£)**	**Overall Cost (£/yr)**
Consumables (Mineral Oil)	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
NaOH	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
Catalyst [REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
Catalyst [REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
Catalyst [REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
Plasma Torch Production Fee	[REDACTED CONTENT]	[REDACTED CONTENT]	[REDACTED CONTENT]
Total additional variable operating costs	-	-	[REDACTED CONTENT]

Fixed Operating Costs			
Total Variable OPEX cost	-	-	[REDACTED CONTENT]
-	-	-	[REDACTED CONTENT]
Total Operating Cost (£)	-	-	[REDACTED CONTENT]

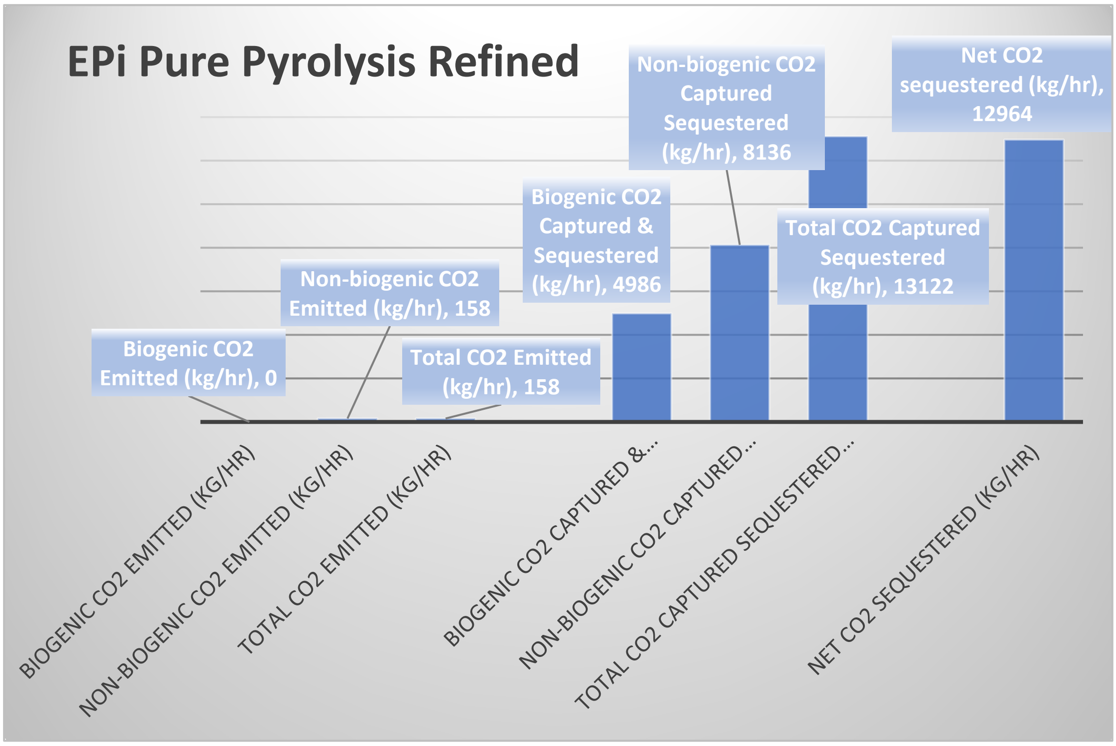


Figure A3-2 1 Total CO_2 emissions emitted and sequestered for 6 EPi Pyrolyser Modules

Table A3-2 4 Net Present Values of the expenditures and revenues

	NPV (£) LCOH Phase 2 (1 year) + 5 Years
CAPEX	[REDACTED CONTENT]
Fixed OPEX	[REDACTED CONTENT]
Variable OPEX	[REDACTED CONTENT]
Gate Fee Revenue	[REDACTED CONTENT]
Carbon Char	[REDACTED CONTENT]
Carbon black	[REDACTED CONTENT]
Carbon cost sequestered	[REDACTED CONTENT]

Table A3-2 5 Levelised costs of the expenditures and revenues

	Levelised Cost (£/MW) Phase 2 (1 year) + 5 Years
CAPEX	[REDACTED CONTENT]
Fixed OPEX	[REDACTED CONTENT]
Variable OPEX	[REDACTED CONTENT]
Gate Fee Revenue	[REDACTED CONTENT]

	Levelised Cost (£/MW) Phase 2 (1 year) + 5 Years
Carbon Char	[REDACTED CONTENT]
Carbon black	[REDACTED CONTENT]
Carbon cost sequestered	[REDACTED CONTENT]

APPENDIX 3-3

DEMONSTRATION AND TESTING RESULTS

LCHS REQUIREMENTS

Table A3-3 1 List of measurements as per LCHS

Measurement Category	Required Data
Energy Inputs	Type, quantity, and energy source (e.g., fossil fuels, renewables).
Process Emissions	Quantified CO_2, CH_4, and N_2O from units like reactors or furnaces.
Carbon Intensity	GHG emissions per kg of hydrogen produced ($kgCO_2e/kg\ H_2$).
Feedstock Data	Quantity, origin, and type of feedstocks (e.g., natural gas, biomass).
Water Use	Total volume and quality of water used in hydrogen production.
Carbon Capture and Storage	Amount of CO_2 captured, storage method, and leakage risk.
Hydrogen Output	Total mass, energy content, and purity of hydrogen produced.
Byproduct Management	Mass and emissions associated with by-products (e.g., carbon black, char).
Electricity Use	Grid intensity, renewable electricity share, and total electricity consumed.
Transport Emissions	Emissions related to feedstock, hydrogen, and byproduct transportation.
Operational Efficiency	Process efficiency metrics (e.g., thermal efficiency).
Infrastructure Emissions	Embedded carbon in construction, installation, and maintenance of facilities.

Table A3-3 2 What and when to report as per LCHS

Stage	Parameter	Details
Before Operation	Infrastructure Emissions	Embedded carbon in construction and equipment setup.
-	Supply Chain Assessment	Emissions from feedstock sourcing and logistics setup.
-	Process Design Efficiency	Predicted thermal efficiency and emissions from the planned process.
-	Baseline Carbon Intensity	Expected $kgCO_2e/kg\ H_2$ based on design assumptions.
During Operation	Energy Inputs	Type, source, and quantity of energy used monthly or per batch.
-	Hydrogen Production	Mass, purity, and energy content of produced hydrogen.
-	Carbon Capture and Storage (CCS)	Amount of CO_2 captured, stored, and monitored for leakage.
-	Byproduct Management	Quantities and emissions related to by-products.
Continuous	Direct Process Emissions	Real-time monitoring of CO_2, CH_4, and N_2O emissions.
-	Water Use	Continuous tracking of water consumption and quality.

Stage	Parameter	Details
-	Operational Efficiency	Ongoing assessment of thermal and process efficiency.
-	Safety and Environmental Compliance	Continuous adherence to operational safety and environmental standards.

PILOT PLANT TEST RESULTS – IMPERIAL COLLEGE & PIMOT LABORATORIES

Table A3-3 3 Gas results of all pilot scale trials

	Trial-1	Trial-2	Trial-3	Trial-4
Data	**AVE**	**AVE**	**AVE**	**AVE**
H_2	33.40%	27.40%	19.59%	41.67%
CH_4	15.90%	18.60%	27.87%	32.50%
CO	26.70%	27.00%	12.57%	7.20%
CO_2	13.40%	19.20%	9.09%	3.17%
Other gases (C_2-C_5)	10.60%	7.80%	30.86%	15.44%
Gross CV (MJ/Nm^3)	20.67	19.2	34.7	29.9
Net CV (MJ/Nm^3)	18.9	17.6	31.9	27.1
Gas density (kg/Nm^3)	0.8725	0.9701	0.9376	0.6244
Gross CV (MJ/kg)	23.63	19.8	37.1	48.2
Net CV (MJ/kg)	21.63	18.1	34.1	43.7
Gross CV (kJ/Nm^3)	20674.86	19215.5	34685.9	29893.9
Net CV (kJ/Nm^3)	18936.84	17605.1	31928.0	27082.9
Gross CV (kJ/kg)	23626.44	19809.1	37076.0	48217.9
Net CV (kJ/kg)	21634.99	18149	34127.5	43673.6

Table A3-3 4 Proximate analysis test results

	Moisture Content, %	Ash Content, %
SRF	3	15.30
Willow Wood	5	0.90
HDPE	0.05	0.07
SRF+HDPE	0.27	0.66

Table A3-3 5 Elemental analysis test results

	C (%)	H (%)	N (%)	S (%)
SRF	43.98	5.73	0.21	0.54
Willow Wood	45.70	5.67	1.44	0.15
HDPE	84.97	14.28	0.49	0.22
SRF+HDPE	71.64	11.23	0.3565	2.135

Table A3-3 6 Feedstock Calorific Value test results

	CV [MJ/kg]		
SRF	19.61	±	1.87
Willow Wood	17.33	±	1.02
HDPE	46.24	±	2.03
SRF+HDPE	37.76	±	1.06

Table A3-3 7 Carbon Char proximate, energy and C, H, N, S test results

	Trial-1	Trial-2	Trial-3	Trial-4
Moisture Content, %	<0.1	<0.1	0.1	1.3
Ash Content, %	66.3	55.5	45.7	69.7
CV, MJ/kg	18.4	16.4	17.6	13.2
C, %	50.3	45.2	50.7	34.9
H, %	0.7	0.8	0.8	0.8
N, %	0.9	0.9	0.9	0.8
S, %	3.2	3.6	3.7	4.2

Table A3-3 8 Mass Balance of all laboratory scale trials (100kg basis)

Mass Balance	Trial-1	Trial-2	Trial-3	Trial-4
Feed	100	100	100	100
Char	17	26	19	10
Gas	74	62	72	83
Oil + Water	9	11	10	7

Table A3-3 9 Outlet Gas compositions for Reactor experiments

	Chromatogram output (molar %, normalised)			
Experiment	H_2	CO_2	CH_4	Sum
1	-	-	-	-
2	61.96	-	38.04	100
3	49.71	-	50.29	100
4	49.63	-	50.37	100
5	51.23	-	48.77	100
6	51.54	-	48.46	100
7	53.99	-	46.01	100
8	52.62	-	47.38	100
9	55.11	3.03	41.85	100
10	50.72	-	49.28	100
11	51.04	-	48.96	100
12	31.02	-	68.98	100
13	50.25	-	49.75	100
14	52.44	-	47.56	100
15	53.51	-	46.49	100

Chromatogram output (molar %, normalised)				
16	-	-	-	-
17	-	-	-	-
18	51.90	-	48.10	100
19	66.60	9.01	24.39	100
20	41.53	-	58.47	100
21	69.72	2.09	28.19	100
22	79.75	17.78	2.46	100
23	80.98	18.07	0.95	100
24	80.88	18.05	1.07	100
25	80.57	18.18	1.25	100
26	81.26	17.58	1.16	100
27	80.65	16.95	2.40	100

Table A3-3 10 Outlet Gas compositions for Catalytic Reactor experiments

GC output (molar %, normalised)					
Experiment	H_2	CO_2	CO	CH_4	Sum
1	43.23 / 42.79	2.76 / 2.88	1.59 / 1.66	52.42 / 52.67	100 / 100
2	44.19 / 44.21	3.27 / 3.4	1.57 / 1.49	50.97 / 50.9	100 / 100
3	43.29 / 43.4	2.85 / 2.86	2.05 / 1.96	51.81 / 51.78	100 / 100
4	44.64 / 44.64	3.19 / 3.2	1.83 / 1.81	50.34 / 50.35	100 / 100
5	43.89 / 44.02	2.87 / 3.01	2.04 / 1.89	51.2 / 51.08	100 / 100
6	44.59 / 44.59	3.28 / 3.25	1.56 / 1.68	50.57 / 50.49	100 / 100
7	45.44 / 45.29	3.31 / 3.43	1.77 / 1.68	49.47 / 49.6	100 / 100
8	44.24 / 44.04	3.44 / 3.52	1.48 / 1.42	50.84 / 51.02	100 / 100
9	43.51 / 43.35	4.83 / 4.81	2.16 / 2.19	49.5 / 49.65	100 / 100
10	44.33 / 44.54	5.24 / 5.27	1.99 / 2.02	48.44 / 48.17	100 / 100
11	47.51 / 47.08	30.41 / 30.61	4.59 / 4.65	17.49 / 17.66	100 / 100
12	46.35 / 46.62	29.83 / 29.7	5.9 / 5.87	17.92 / 17.81	100 / 100
13	44.86 / 44.86	3.15 / 3.21	1.94 / 1.86	50.05 / 50.07	100 / 100
14	46.02 / 45.92	3.93 / 3.99	1.13 / 1.15	48.92 / 48.94	100 / 100
15	46.2 / 46.09	3.92 / 3.92	1.11 / 1.11	48.77 / 48.88	100 / 100
16	32.73 / 32.59	11.33 / 11.44	0.89 / 0.79	55.05 / 55.18	100 / 100
17	33.88 / 33.7	12.02 / 12.29	0.5 / 0.57	53.59 / 53.44	100 / 100
18	33.7 / 43.51	12.29 / 3.33	0.57 / 1.6	53.44 / 51.57	100 / 100
19	43.51 / 43.31	3.33 / 3.73	1.6 / 1.64	51.57 / 51.32	100 / 100

Table A3-3 11 Outlet Gas compositions for Catalytic Reactor experiments

GC output (normalised)					
Experiment	**H_2**	**CO_2**	**CO**	**CH_4**	**Sum**
1	44.93 / 44.52	3.75 / 3.85	0.9 / 0.94	50.42 / 50.69	100 / 100

	GC output (normalised)				
2	44.66 / 44.49	4.24 / 4.19	0.38 / 0.42	50.72 / 50.9	100 / 100
3	45.62 / 45.41	4.49 / 4.65	0.28 / 0.28	49.61 / 49.66	100 / 100
4	44.84 / 44.77	4.54 / 4.43	0.15 / 0.11	50.47 / 50.69	100 / 100
5	45.42 / 44.98	4.47 / 4.79	0.14 / 0.04	49.98 / 50.2	100 / 100
6	44.46 / 44.31	4.43 / 4.51	0.13 / 0.12	50.99 / 51.07	100 / 100
7	44.98 / 44.91	4.42 / 4.59	0.14 / 0.09	50.46 / 50.41	100 / 100
8	44.85 / 44.83	8.98 / 8.77	0.77 / 0.7	45.4 / 45.7	100 / 100
9	43.75 / 43.78	8.56 / 8.45	0.66 / 0.63	47.03 / 47.15	100 / 100
10	46.22 / 46.44	4.77 / 4.83	0.13 / 0.04	48.87 / 48.7	100 / 100

Table A3-3 12 Output gas composition from catalytic reactor

Experiment #	GC output (normalised, molar %)		
-	H_2	CO_2	CH_4
28	34.46	0.00	65.54
29	21.39	0.00	78.61
30	8.73	0.00	91.27
31	33.97	0.00	66.03
32	34.67	0.00	65.33
33	21.52	0.00	78.48
34	8.45	0.00	91.55
35	33.14	0.00	66.86
36	20.73	0.00	79.27
37	8.30	0.00	91.70
38	8.52	0.00	91.48
39	10.61	0.00	89.38
40	26.93	0.00	73.07
41	34.53	0.00	65.47
42	21.44	0.00	78.56
43	8.63	0.00	91.37

APPENDIX 3-4
UPDATED CARBON LIFE CYCLE ASSESSMENT OF THE TECHNOLOGY

Table A3-4 1 Summary table of the key assumptions and data used in the carbon assessment model

Assumption/ Data	Details	References / Sources
Plant Availability	7800 hours/year	EPi
Maximum Feed Rate	1 tonne/hour of SRF material	EPi
Pyrolysis Unit	Model based on one pure pyrolysis unit	EPi
Gas Refinery	LCA calculation based on one GR	EPi, Siemens
Plasma Torch	LCA calculation based on 35 PT	HiiROC
Feedstock Composition	Mixture of SRF and waste HDPE (from MSW after removing inert and recyclable components)	EPi
Mass Balance		
- Syngas Production	0.800 tonnes/tonne of SRF	Based on pilot plant tests and gPROMS simulations:
- Char Production	0.100 tonnes/tonne of SRF	Based on pilot plant tests and gPROMS simulations:
- Hydrogen Production	0.196 tonnes/tonne of SRF	Based on pilot plant tests and gPROMS simulations:
- Carbon Black Production	0.548 tonnes/tonne of SRF	Based on pilot plant tests and gPROMS simulations:
- CO_2 Emissions	0 tonnes/tonne of SRF	Based on pilot plant tests and gPROMS simulations:
Carbon Content of SRF	71.64% (by weight)	Imperial College test results
Biogenic Carbon Fraction of SRF	Calculated as 38% (by weight)	Alfred H Knight Energy Services Ltd
Carbon Content of Char	51% (by weight)	Imperial College test results
Syngas Carbon Content	Calculated from component mass fractions, molar mass, and number of carbon atoms	gPROMS data for mass fractions Molar Mass, Molecular Weight and Elemental Composition Calculator
Energy Content of Feedstock	SRF: 37.76 MJ/kg, Char: 17.6 MJ/kg	Imperial College test results
Energy Content of Syngas		Calculated from component gases' calorific values based on Imperial College GC results.
Parasitic Electrical Load	Maximum load of 2188 kWe, with 75% utilisation factor, equating to 1641 kWe electrical consumption	EPi, GR suppliers, HiiROC
Energy Consumption	1641 kWe for 7800 hours/year, totalling energy consumption based on operational hours	EPi, GR suppliers, HiiROC
Electricity Supply	Assumed to be supplied externally from the grid	EPi
Natural gas carbon intensity	0.204 tonnes/MW	Treasury Green Book Table 2a, converted from gross to net CV by dividing with 0.903445, based on https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

Assumption/ Data	Details	References / Sources
Grid Carbon Intensity	0.136 tonnes CO2/MWe	HM Treasury Green Book Data 2023
Biogenic Carbon Emissions	Treated as neutral (sequestered during organic lifecycle)	Arup
Char and Carbon Black Sequestration	Carbon is stored in char/Carbon Black; negative emissions assumed if not combusted	Arup
Exclusions	Operational and transport emissions, negative emissions from hydrogen production	Arup
LHV of Hydrogen	120 MJ/kg	Heat of combustion - Wikipedia

[REDACTED CONTENT]

Figure A3-4 1 Carbon Assessment Model-data

[REDACTED CONTENT]

Figure A3-4 2 Carbon Assessment Model-calculations