Genesis Control Systems (UK) Ltd

HYDROGEN BECCS INNOVATION PROGRAMME: PHASE 1

FINAL REPORT

Environmental Power International (UK) Ltd &
Project Partners

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List of Abbreviations and Symbols

Abbreviation	Definition
BOM	Bill Of Material
C	Carbon
C&D	Construction and Demolition Waste
C&I	Commercial and Industrial Waste
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamics
C-H	Methyl alkyl (Carbon-Hydrogen bonds)
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EPi	Environmental Power International Ltd.
FAT	Factory Acceptance Test
FMEA	Failure Mode and Effect Analysis
GTL FT	Gas to Liquid Fischer-Tropsch
H	Hydrogen element
H_2	Hydrogen
HDPE	High Density Polyethylene
WGS	High Temperature Low Temperature Water Gas Shift Reactor
kWe	Kilowatt Electric
LCA	Life Cycle Assessment
LCOH	Levelised Cost of Hydrogen
MCC	Motor Control Centre
MR	Methanation Reactor
NA	Not Available
NPV	Net Present Value
O&M	Operations and Maintenance
OPEX	Operating Expenditure
PSA	Pressure Swing Adsorption
PT	Plasma Torch
RAMS	Risk Assessment Method Statement
SERC	Sustainable Energy Research Consortium
SRF	Solid Recovered Fuel
T	Temperature
T&S	Transport & Storage
TBC	To Be Confirmed
TRL	Technology Readiness Level
WGS	Water Gas Shift

1. EXECUTIVE SUMMARY

Environmental Power International (UK) Ltd, supported by a wider team of specialists from both industry and from academia, investigated how to maximise production of hydrogen through pyrolysis of waste and/or biomass material while achieving net negative CO_2 emissions. Our unique Pure Pyrolysis Technology aimed to deliver the core objectives of the BECCS programme (1) reduce levelised cost of hydrogen (LCOH) production (2) improve efficiencies associated with Hydrogen BECCS technologies, (3) improve syngas treatment technologies to effectively control contaminant concentrations to improve pyrolysis/gasification process performance and (4) develop syngas upgrading technologies, which can be combined with CCS, to improve the LCOH production.

The Pure Pyrolysis Refined Project was made up of several work packages exploring the performance of conventional and novel hydrogen production processes in terms of H_2 yields and CO_2 emissions, the flexibility of these configurations to work with a wide range of feedstock, the levelised costs of hydrogen production associated with the selected configuration and the preparatory work conducted to bring the proposed process to commercial readiness.

There are several configurations which can deliver hydrogen production from waste and biomass. This Project considers the use of EPi's high temperature pyrolyser followed by a five-stage gas conditioning unit to produce a high-quality fuel gas. The patented internal drive mechanism and the exceptional control over the characteristics of the process heating to demonstrate that the EPi pyrolysis technology has the flexibility to operate on a wide range of feedstocks.

EPi's pyrolyser has been extensively tested on many waste and biomass streams including SRF derived from MSW, C&I and C&D, dried sewage sludge, woodchip and meat and bonemeal. The additional advantages of the use of the EPi pyrolysis are that the unique process has no airborne emissions; and enables part of the carbon in the feedstock to be captured in the form of a solid Carbon Char, suitable for use in a number of applications. EPi has built, operated, and tested 5 full size demonstrator plants over a period extending to more than twenty years, bringing the technology to pre-commercial stage with a Technology Readiness Level (TRL) of 7.

The fuel gas produced in the pyrolyser already high in Methane, is further modified into an elevated methane content using a carbon dioxide scrubber, integrated with CO_2 Catalytic Methanation and HT & LT Water Gas Shift reactors. This combination further enhances the methane content of the final gas product. The gas is finally filtered through a series of Membrane filters prior to presentation to an advanced plasma technology for the final stage of hydrogen production. The systems utilised to elevate the methane content in the gas stream are mature technologies each of which has a high TRL.

The Plasma Torch converts the methane rich gas by splitting the hydrocarbon molecules into its base components: hydrogen and carbon. In the absence of oxygen, the high-speed process shares some key characteristics with the EPi pyrolysis in that it has no emissions. Carbon is captured through the process in the form of a solid Carbon Black.

The final configuration for the design was determined as a result of a number of workshops carried out with collaborators from academia and industry, 15 simulation studies using gPROMS™ and operations on a test rig carried out at Imperial College, specifically designed to emulate key aspects of the EPi technology. Research and design criteria initially focused on hydrogen stripping technologies and production processes, in order to identify complementary technologies for integration with the EPi pyrolyser. The final criteria in determining best options from the proposed technologies and configurations involved:

1. Maximising hydrogen production
2. Minimising CO_2 emissions and maximising carbon capture

3. Toleration of changes to feedstock to operate on a wide range of biomass and waste streams
4. Maximising conversion of waste to useful products
5. Minimising capital and operational costs.

All of the configurations were modelled using gPROMS™ computer modelling based on the gas results received from the Pyrolysis test rig at Imperial College. This rig had previously been constructed specifically to emulate some of the key working principles of EPi's pyrolysis process. The test rig was operated on a variety of feedstocks with biogenic content ranging from 38% to 84%. Both conventional and novel approaches were simulated using information taken from the trial data, literature reviews, and matched to historic performance data taken from extended operations of EPi's full scale demonstration facility which had previously operated between 2010 and 2014. The final configuration was also validated by a series of secondary modelling exercises (CFD model) carried out by the plasma torch provider. The results of the modelling work are summarised in Tables 2 and 3 in Section 2 below.

The final configuration was determined, following a series of multi-stage modelling exercises. Each configuration modelled in the early stages could achieve hydrogen production with varying levels of CO_2 emissions. As one of the most critical objectives was to reduce the emissions, CO_2 scrubbers were introduced in the later stages of development. New configurations were further complemented with the inclusion of Water Gas Shift Reactors and a CO_2 MR to decrease the oxygenated compounds in the gas stream, thereby enabling higher yields of both Hydrogen and Carbon Black.

Whilst a number of the configurations could achieve low emissions and produce hydrogen, further research combined with extended analysis identified that enhanced amounts of hydrogen and Carbon Black could be produced from the final configuration proposed. Additionally, the aim was to improve the levelised cost of Hydrogen produced from a same size plant. For this purpose, the feedstock used during the pilot plant trials was changed from a mixture of SRF and willow wood (biogenic content 84%) to a blend of SRF and waste plastics (biogenic content 38%).

The final stage testing on the mixture of SRF and plastics and the subsequent simulation studies on the selected configuration indicated that 1 tonne of waste can be converted into 182.8 kg of gas, 90.13% of which is pure hydrogen amounting to 164.7 kg of hydrogen per hour. In addition to that, the proposed design provides substantial opportunity for Carbon Capture through its by-products, including 523.6 kg/hr of solid Carbon Black and 100 kg/hr of solid Carbon Char. Carbon capture in the form of solid carbon is highly desirable as the challenges of achieving capture and storage of carbon in gaseous form are well documented and accepted as both challenging and costly.

Our results conclusively demonstrated the potential for substantial increases in the yields of hydrogen and Carbon Black and thus the associated levelised costs of hydrogen. It was also significant that the results clearly demonstrated that the proposed configuration was sufficiently flexible to operate on various blends of waste streams as might be required as a result of ever changing market conditions.

Following determination of the final design configuration, a carbon Life Cycle Assessment (LCA) was undertaken in conjunction with Ove Arup in order to evaluate the wider environmental impact of the proposed configuration. The results demonstrated that EPi's Pure Pyrolysis Process operating on the mixture of SRF and waste plastics is found to release 0.057 tonnes/hr carbon dioxide emissions to atmosphere, of which 0.013 tonnes/hour is biogenic and can therefore be treated as neutral, resulting in 43 kgs of carbon dioxide emissions to atmosphere every hour. The offset is that the process captures 2.093 tonnes/hr of carbon dioxide in Carbon Char and Carbon Black, of which 0.795 tonnes/hr is biogenic and therefore can be treated as negative. By this rationale, the process results in 0.752 tonnes/hour net negative emissions. The results underline that the benefit is greater in terms of CO_2 emissions for the less oxygenated waste streams and provides a strong motivation to develop the technology.

Net Present Value (NPV) and Levelised Cost of Hydrogen (LCOH) analyses have been carried out based upon a typical commercial scale EPi installation which, due to operational efficiencies and optimal system configuration would typically consist of 6 EPi modules. The levelised cost of Hydrogen (LCOH) for the current design is calculated as being well below the current target threshold of £86.8 /MWh over 5 year-period based upon a typical commercial scale operation. The LCOH reduces further to a £ per /MWh value continues to yield values substantially lower than the target threshold with further reductions in cost achieved over 10- and 25-year periods respectively. The sensitivity of LCOH to carbon values has been analysed by using the higher carbon values, obtained from the Green Book's Central Case scenario. As the carbon value for sequestered carbon increases, the LCOH is reduced radically over 3 + 5-year period of a 6 module EPi plant.

EPi is currently part way through manufacture of its 7th Generation pyrolysis module to convert SRF waste into pyrolysis gas. Designs for the integrated plant which will convert pyrolysis gas into hydrogen have been developed in readiness for full system integration. The PFDs and P&IDs have been designed and vendors have been selected for each major manufacturing package. A project plan for the delivery of the single module reference plant has been prepared which entails:

- The detailed design for the complementary technologies to be completed in Q3 2023
- Equipment to be delivered to site not later than Q1 2024
- Installation & Commissioning of the integrated H_2 system be completed by Q3 2024
- The integrated single module Plant to have been operational for around six months by Q4 2024

EPi has enjoyed the support of it's long term partnerships with Bilfinger and Siemens as delivery and technical support partners, and in preparation for the roll out of this technology solution, have also identified a range of outlets for the process outputs, as well as sources of supply for materials as required for manufacture. Agreements in principle are also in place for procurement of the feedstock.

EPi has been involved in various planning applications over the years at various sites around the UK. These applications also include a recent planning application approved in September 2021 for a waste to energy facility on a green field site, Nr Chelmsford through Essex CC. With the sole exception of the site in Chelmsford all applications were passed in less than 14 weeks from date of submission. The Chelmsford application took circa 17 weeks due to staff shortages and cancelled planning meetings caused by the Covid Lockdown. In addition to the Chelmsford site, EPi has also located three alternative sites suitable for deployment of a single module reference plant, all of which have scope to extend operations to a full scale 6 module commercial installation.

A summary of activities and outcomes of the Phase 1 studies to reach the project target have been presented in Figure A1 in Appendix 1. The following sections provide a summary of activities and outcomes of the Phase 1 studies to reach the project targets. EPi is comfortable that the project met the programme Phase 1 requirements successfully and is ready to move to Phase 2, to provide the technology configuration deliver the performance, efficiencies and outputs as identified in Phase 1.

2. SCIENCE AND ENGINEERING

Extensive detailed literature reviews and scientific research for potential hydrogen production and carbon removal technologies have been undertaken during Phase 1. In addition to that, a series of engineering studies to find the best and optimal design configuration, through assessment of energy generation potential, yields and production requirements have been performed. Since the award of contract, the feasibility assessment has been carried out in four distinctive but correlated steps.

During the first phase of our works, the aim was to identify and assess a range of proven technologies which could convert and/or strip the pyrolytic gas into hydrogen and other gases. Technologies studied included GTL FT, WGS, PSA, Amines Plant, CO_2 Catalytic MR and Plasma Torch. Seven configurations were created by using different combinations of each of the technologies assessed. Subsequently, the hydrogen yield and CO_2 emissions associated with these configurations were determined using advanced computer modelling; gPROMS™ Process 2.2 Mathematical modelling, simulation, and optimisation packages. As a result, two configurations were initially shortlisted for more detailed evaluation (Options 5 and 7 in Tables 2 and 3). Option 3 was dismissed even though, at that time, this delivered the highest hydrogen yield as this configuration led to the highest CO_2 emissions. Option 5 produced the second highest hydrogen however, once again with very high CO_2 emissions. The third highest hydrogen yield was obtained with Option 7 with the lowest CO_2.

Throughout the second step of the Project, further literature review and discussions with experts in the field were conducted to identify the factors which influenced gas composition and product yield. This study was carried out to ascertain the optimal operating conditions for the pyrolysis unit which could deliver a gas composition most suited to effective operations within the downstream processes in order **to achieve the highest yields of hydrogen whilst reducing CO_2 emissions.** It was determined that feedstock composition and characteristics including oxygen content, particle size, moisture content, inert content and C-H ratio had a significant influence on the gas composition. At the same time, operating conditions such as the residence time, initial heating rate and the wider temperature regime as applied within the pyrolysis chamber, all played an important role in the final product distribution and composition. Consequently, it was agreed that a combination of the above factors would be trialled at the test rig at Imperial College.

The findings of the literature review and discussions carried out in the first two steps were combined in the third step of the Project which led to the inclusion of three additional processes: CO_2 methanation phase, WGS Reactors and the CO_2 Stripping Phase. As a result, six more configurations were studied to determine the first of our engineering design proposals. These are presented as options 5a, 7a, 7b, 8, 9 and 9a in Tables 2 and 3 below. The results showed that the new configurations could lead to seven times less CO_2 emissions (Options 1-4 in Table 3). All these options were assessed during workshop 3 and **Options 7b (with GTL FT) and 9a (without GTL FT) were shortlisted for further investigation. The o**ptions incorporating the CO_2 Stripping phase were favoured over many of the alternative options. Please refer to Section 2.1 for a detailed process description.

Simultaneously with the above modelling and reviews, laboratory scale trials were conducted at Imperial College to assess the impacts of various factors identified in the first two steps. Trials confirmed the characteristics that mostly impacted the product yield (mass balance) and those that had a smaller impact on the gas composition whilst further tests verified the importance of the influence of feedstock characterisation on gas composition. Simulations were run on the selected configurations based on these gas results. Despite the reductions in CO_2 emissions, low hydrogen yields necessitated further analyses. The results clearly indicated that a methane rich syngas was a required condition, in order to increase hydrogen production in this particular configuration.

Therefore, the **fourth stage involved laboratory trials, conducted at Imperial College to assess the impacts of the factors identified in the first three steps. The feedstock trialled during the fourth stage was an SRF + Plastic mix containing less oxygen with more C-H bonds (biogenic content 38%).** This mixture was selected due to its commercial availability and to facilitate the recovery of a range of waste plastics. Further trials were successful in confirming the assumptions previously made; a methane rich syngas with lower CO and CO_2 content could be produced with less oxygenated feedstock.

The data from two sets of laboratory trials, using low and high oxygen content feedstock, at low and high temperature are presented in Table 1 and Figure 1 below. Methane content was increased by 49.8% and CO and CO_2 were reduced by 53.7% and 52.6% respectively when low oxygen containing feedstock was used. To achieve further increases in methane and hydrogen yields as well as gas conversion ratio, various changes were made to the process characteristics applied during the Pyrolysis phase. The Methane content of the syngas was now 51% higher than the methane content of the syngas produced from earlier trials with the previous SRF mix, when both trials were conducted using the same temperature regime. Further minor changes in process characteristics during the Pyrolysis phase showed that the methane yield in the syngas could be increased by a further 4.63%. Similar improvements in CO and CO_2 ratios were observed where the total amount of CO and CO_2 in the syngas decreased from 21.66% to 10.37% when other changes to process conditions in the Pyrolysis phase were applied. Table 1 and Figure 1 below demonstrate the increase in H_2 and CH_4 production in exchange for the decrease in CO and CO_2.

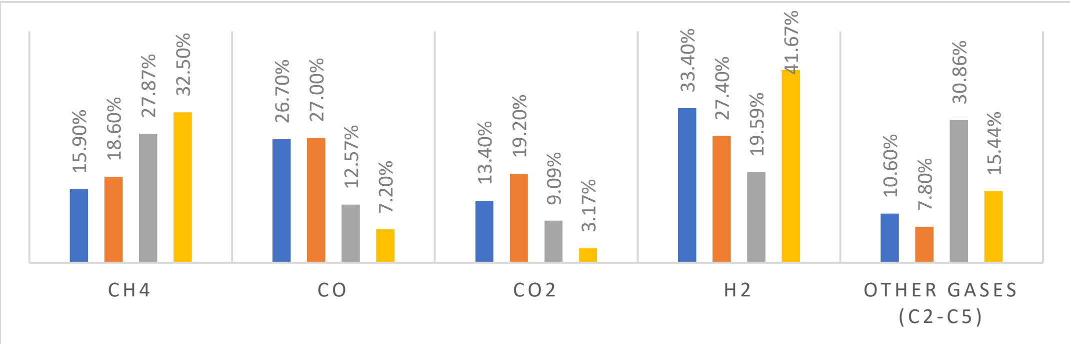

Figure 1 Comparison of Gas results from different feedstock and operating conditions within the Pyrolysis phase.

	06.09.22	07.09.22	28.09.22	29.09.22
Feedstock Type	SRF (containing high oxygen content)		SRF (containing high C-H content)	
Pyrolysis Phase.	Process Characteristics 4.2	4.4	5.8	Process Characteristics 5.3
Data	AVg	AVg	AVg	AVg
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%
H_2	33.40%	27.40%	19.59%	41.67%
Other gases (C_2-C_5)	10.60%	7.80%	30.86%	15.44%

Simulation studies were repeated for Option 7b and 9a by using the results obtained from our various trial data to see the effect of feedstock and Process characteristics on the shortlisted configurations. The results revealed significantly higher H_2 yields with minimum amounts of CO_2 emissions. The selection of Option 7b was made based on the simulation results which were achieved by using gas composition that was available from previous EPi pyrolysis trials, where the feedstock had been produced from differing specifications of SRF. Some of these results showed a gas composition with an ideal CO:H_2 ratio suitable for operations in GTL FT units. But the trials using the test rig at Imperial College with the actual feedstock have demonstrated differences in the CO:H_2 ratio in the gas composition. Subsequent simulations based upon the new gas data, demonstrated that higher yields of hydrogen could be achieved by omitting the GTL FT units.

As a result, Option 7b was subsequently dropped from our options under consideration, as the primary objective of this project is to increase hydrogen production while minimising the levelised costs of hydrogen and capturing carbon, and Option 9a was therefore selected as the proposed configuration for hydrogen production. As a result the planned tests with the GTL FT units were cancelled and replaced with simulation studies which modelled the requirements for the actual design and operations of the proposed system. The hydrogen yield calculated by the simulations was also verified by a different computerised model (CFD) conducted by the providers of the plasma torch.

Finally, the two data sets obtained from the trials carried out under differing characteristics within the pyrolysis phase were simulated on the selected configuration: Option 9a. The simulations 9a_1 and 9a_demonstrated a substantial increase in hydrogen production and significant reductions in CO_2 emissions. In line with the earlier expectations 9a_2 has become the preferred option as it led to the highest yields of hydrogen with lowest CO_2 emissions. The process flow block diagram of this selected configuration is presented in Figure 7 below. **This configuration indicates that 1 tonne of waste can be converted into 182.8 kg of product gas, 90.13% of which is pure hydrogen amounting to 164.7 kg of hydrogen per hour.** At the same time, this option releases only 34.78kg/hr of CO_2 from the process **which equates to 0.21 kg of CO_2 for every kg of hydrogen produced.**

To summarise, throughout the project, fifteen different configurations were designed and studied with the aid of simulations run on gPROMS™ computer modelling to determine the best possible configuration to produce highest yields of hydrogen while minimising the carbon emissions and maximise the capture of carbon. The configurations studied and distributions of the associated products including hydrogen, Carbon Black and CO_2 emissions are presented in Tables 2 and 3 below.

Table 1 Plant operation units per each configuration

OPTIONS #	Plant operation units					
1	EPi pyrolysis	CO2 Stripping Option 1	WGS reactor			
2	EPi pyrolysis	GTL FT				
3	EPi pyrolysis + steam	CO2 Stripping Option 1	WGS reactor			
4	EPi pyrolysis + steam	GTL FT	Membrane			
5	EPi pyrolysis	GTL FT	CO2 Stripping Option 2	PT CH_4		
5a	EPi pyrolysis	GTL FT	WGS	CO2 Stripping Option 2	PT CH_4	
6	EPi pyrolysis	GTL FT	CO2 Stripping Option 2	PT CH_4	PT CO_2 with CH_4 co-reactant	
7	EPi pyrolysis	GTL FT	CO2 Stripping Option 2lant	PT CH_4	CO_2 MR	
7a	EPi pyrolysis	GTL FT	WGS	CO2 Stripping Option 2	PT CH_4	CO_2 MR
7b	EPi pyrolysis	GTL FT	CO2 Stripping Option 3	WGS	PT CH_4	CO_2 MR
8	EPi pyrolysis	WGS	WGS	CO2 Stripping Option2	PT CH_4	CO_2 MR
9	EPi Pyrolysis	CO2 Stripping Option 2	WGS	WGS	PT CH_4	CO_2 MR
9a	EPi Pyrolysis	CO2 Stripping Option 3	CO_2 MR	WGS	PT CH_4	
9a_1	EPi Pyrolysis	CO2 Stripping Option 3	CO_2 MR	WGS	PT CH_4	
9a_2	EPi Pyrolysis	CO2 Stripping Option 3	CO_2 MR	WGS	PT CH_4	

Table 2 Simulation Results of Several Configurations for H_2 production

Output Data	CONFIGURATIONS #													
	1	2	3	4	5	5a	6	7	7a	7b	8	9	9a	9a_1	9a_2
Hydrogen [kg/h]	19.4	0	62.1	35	57.2	58.5	50 -> 7	43 -> 29	32.7	32.3	35.4	38.6	38.3	96.2	182.8

Syncrude [kg/h]	0	40	0	64	40	40	60 -> 178	40	40	40	0	0	0	0	0
CO_2 (plant internal)	1076	956	1108	879	342	335	302 -> 4	177 -> 12	52	49	18	52	49	49	34.78
Carbon Black [kg/h]	0	0	0	0	166	168	160 -> 141	211 -> 256	245	246	288	279	279	444	523.6
Water [kg/h]	0	68	-198	-83	68	50	106 -> 329	195 -> 323	289	355	716	368	638	118	88.5

The decision criteria and background to the lab tests and simulation studies are demonstrated in the Figure 2 below.

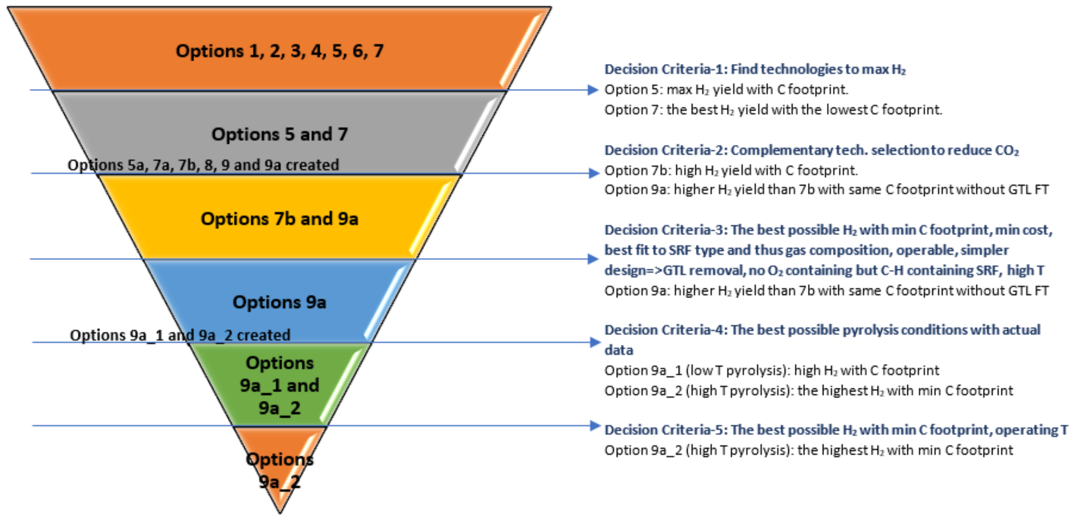

Figure 2 Decision pyramid for the best configuration

Thus, it is concluded that the optimum design that can deliver the objectives of this project entails high temperature pyrolysis of less oxygenated feedstock processed in a configuration which integrates the following processes: High temperature pyrolyser, CO2 Stripping & Recovery, WGS, CO_2 Catalytic MR, Membrane Filtration, Methane Plasma Torch.

2.1. PROCESS DESCRIPTION

EPi is a UK technology provider who has developed a Pure Pyrolysis Process for the treatment of various material streams over 24 years. The fully patented process is robust and easy to scale up due to its modular design. The process provides flexibility in terms of the feedstock types and has been tested on various waste streams ranging from different mixtures of feedstock with high and low biogenic content (H2BECCS trials were conducted on blends with 38% - 84% biogenic content), to SRF derived from MSW, C&I and C&D, woodchip and sewage sludge. Process parameters including the feed rate, residence time and heat regime are easily adjustable to obtain different product yields including high levels of hydrogen.

The product yield (gas, Carbon Char, centrifuge cake) depends heavily on the material being used and the temperature and residence time of the operation. The EPi process is exceptional in that it operates at a much higher temperature than similar processes and thus is capable of shifting the gas production up to 80% of the feed, with little liquid being produced. Please refer to Figure 3 to see a snapshot of EPi's pyrolysis system.

EPi's pyrolysis system is mainly composed of 4 sub-systems:

Feeding System	The feedstock is stored in dual gravity fed hoppers and subsequently fed continuously to the main pyrolyser via means of a triple auger system.
Pyrolyser	Decomposition of input material in the absence of oxygen (no combustion).
Char Extract	The Carbon Char together with fine carbon particles captured in the cyclone are recovered by the char extract assembly which moves the char to interim storage.
Gas Conditioning	The gas produced in the pyrolyser is subjected to a 5-phase cleaning and conditioning unit to produce a clean, high quality fuel gas, suitable for use in a gas engine or turbine. The gas leaves the main pyrolysis chamber at high temperatures before passing through a cyclone to assist in the removal and reduction of any small quantities of particulate matter, that may have been caught up in the gas flow. The core pyrolysis phase is applied in a more controlled manner than many other technologies, resulting in an output gas that is considerably less contaminated by solid particles than that produced by other thermal treatment processes. The EPi process would typically operate at pressures of less than 70 - 90 millibar, however, the downstream processes benefit from elevating the process pressure to between 100 and 150 millibar. Most, if not all, other processes use large pumps or extract fans to pull the gas from the main chamber, thereby pulling high volumes of solid particles into the gas stream. EPi's process has been designed in the reverse manner, utilising natural aspiration to simply vent the gas by means of its own pressure. EPi's gas stream is therefore far cleaner and far less likely to contain solid matter than other processes. However, the volume of gas produced is such that the velocity at which the gas exits the main chamber causes ultra-fine particles of carbon to be carried out in the gas stream.
Liquid Filtration	The liquid media used in the Gas Conditioning Unit, are filtered in the Liquid Filtration Unit, and then sent back to the Gas Conditioning Unit for reuse. Sludge cake obtained from filtration is collected separately. This material has a high calorific value and will be re-introduced into the pyrolysis feed system, to be mixed with the incoming feedstock. This will provide an additional opportunity to recover the carbon in the char recovery phases and convert any residual energy from the liquid media, back into gas.

Figure 3 Snapshot of EPi Pyrolysis System

The proposed configuration for the Pure Pyrolysis Refined project is designed to operate as follows;

- High CV Syngas is produced from various wastes in EPi's high temperature pyrolysis system
- The cleaned and conditioned syngas then passes to the CO_2 separation and stripping phase where the carbon dioxide is removed.
- CO_2 elements of the gas (99.96 mass%) from the above phase is then passed to the **Catalytic MR** unit for conversion to CH_4.
- Remaining elements of the gas stream are further modified via means of dual phase **WGS reactions** for the conversion of syngas into further hydrogen and carbon dioxide.
- The output gases from these combined phases are then passed through membrane filters for final conditioning, prior to delivery to the Plasma Phase.
- The Plasma Torch splits the hydrocarbon molecules into its base components, i.e. hydrogen and carbon.
- The hydrogen is subsequently quenched in a reaction chamber in preparation for collection and storage. The plasma phase takes place in the complete absence of oxygen, and similar to the EPi technology this high-speed process also has no emissions.
- Carbon capture occurs in the process itself, requiring no additional cost from a requirement to try to effectively store carbon in a gaseous form. The unique and innovative technology vaporises the carbon eliminating the inherent problem of carbon sitting which hinders other methane pyrolysis technologies. Solid, pure Carbon Black is produced which can be used in a variety of commercial applications such as production of tyres, rubbers and plastics, inks, and toners. It is also has commercial uses in the production of steel, cement, and concrete industries. The current methods of production of Carbon Black create emissions, not only of CO_2 but also CH_4 and other greenhouse gases such as N_2O.
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2.2. MASS AND ENERGY BALANCES

The EPi Integrated Technology produces the following outputs.

- Carbon Char from EPi Pyrolysis phase
- Centrifuge cake from EPi Pyrolysis phase
- A high quality energy rich gas from the Pyrolysis phase.
- Heat Energy for further energy generation or localised environmental applications.
- Carbon Black from the Plasma Torch phase
- High quality Hydrogen Gas Output from Plasma Torch phase
- Additional Heat Energy for further energy generation or localised environmental applications.

Table 4 below demonstrates the mass balance achieved based on the results from the lab-scale trials and the simulation studies. Lab trials indicate that while 83% of the input is converted into pyrolysis gas, 10% of the input is converted into Carbon Char. Subsequent simulations run on gPROMS™ Process 2.2 illustrate that 182.81 kg/h hydrogen and 523.6 kg/h Carbon Black are produced from 830 kg/h pyrolysis gas which is produced from 1000 kg/h feedstock. Total CO_2 emissions associated with the process amount to 34.78 kg/hr. A Process Flow Diagram including mass balance is presented in Figure 7 below.

Table 3 Mass Balance

Plant operation units / KPIs	EPi Pyrolysis, **CO_2 Stripping & Recovery**, WGS, Catalytic MR, Membrane, PT
OPTION #	9a_2
Input, kg/h	
Feedstock	1000
Water to WGS	155
Total In	1155
Output, kg/h	

Carbon Char	100
Pyrolysis Oil (Centrifuge cake)	70
Product Gas (Hydrogen)	182.81
CO_2 (plant internal)	34.78
Carbon Black	523.6
Water	243.5
Total Out	1154.69
Difference=Out-In (kg/h)	-0.31

Approximately 10% of the input is converted into Carbon Char at the end of the pyrolysis phase. Carbon Char is a by-product with 17.55 MJ/kg energy content although dependent upon the feedstock this figure can increase substantially to around 30.15 MJ/kg. It has a minimal moisture content of 0.13%. Carbon Char is mainly carbon and contains (0.8%) H, (0.9%) N.

It must be noted that properties of the Carbon Char as well as the quantity of Carbon Char produced is highly dependent on the feedstock used in the process and the operating characteristics of the pyrolysis phase. Carbon Char provides a great potential to capture and sequester carbon.

Additional to the Carbon Char, a further 7% of the input is collected as **centrifuge cake** from the EPi gas cleaning and conditioning system. It has a very high calorific value, nearly 38 MJ/kg which offers opportunities for use as a fuel. The amount of cake produced and its properties such as CV are subject to change based upon the process conditions and feedstock type.

The initial intent is to reprocess this material within the pyrolysis chamber in order to recover further energy back into the gas stream and recover the clean carbon. We will however undertake further investigations as to the commercial potential of this centrifuge cake as we believe the carbon content could potentially yield far greater commercial opportunities than the standard Carbon Char output. Current indications suggest that the fine carbon dust contained within this material may well be Graphene or Carbon C60.

Carbon Black produced in the Plasma Torch is a valuable product which provides good opportunities for carbon capture and sequestration. The structure of Carbon Black changes depending on how quickly it is cooled down once it is produced in the plasma torch. This will influence which of the many uses it can be applied to. Carbon Black is a pure carbon, and its energy content is circa 33 MJ/kg.

Product Gas produced by the Plasma Torch is composed of mostly **H_2** (90.13%). The results of the simulation indicating the product gas composition is presented in Table 5 below. Please note that plasma torch is different from other catalytic reactors, so if the upper limits of CO and CO_2 are not exceeded, 100% methane conversion is achieved.

Table 4 Product gas composition of PT product

Component	Mass %
H_2	90.13
CH_4	0.00
CO	0.00
CO_2	0.00
N_2	8.472528E-4
C_2H_6	0.00
C_3H_8	0.00
C_4H_{10}	0.00
C_5H_{12}	0.00
C_2H_4	0.00
C_3H_6	0.00
Already H_2O	9.78%

The high quality of hydrogen produced by the plasma torch means that we have a high value product. Additionally, the other factor affecting income levels is the “colour” classification of the Hydrogen, depending upon the method of production and the source of any material or energy utilised. This question is under considerable scrutiny at present and various UK, European and Global institutions are currently assessing various factors in order to develop an International recognised standard for classification. As far as we are aware this is yet to be determined, but commercial clients with whom we have been in discussion have already agreed to purchase our hydrogen production at commercially acceptable rates. This client will also provide the necessary on-site storage facilities to assist us, as we develop and increase our production capacities. Please refer Section 4 for the commercialisation of products.

Table 6 below indicates the energy balance of the final design proposal. Please note that the heat losses and the final energy balance will be updated following the discussions with the vendors during Phase 2.

Table 5 Energy Balance

Plant operation units / KPIs	EPi Pyrolysis, CO2 Stripping & Recovery, WGS, Catalytic MR, PT		
OPTION #	9a_2		
	Input	*CV, MJ/kg*	Energy In, MJ/h
Feedstock, kg/h	1000.00	37.76	37760.00
Water to WGS Reactors, kg/h	155.00	0.00	0.00
Electricity Input (kWh)	1834.69	NA	6604.88
Total Energy In, MJ/h			**44364.88**
	Output	*CV, MJ/kg*	Energy Out, MJ/h
Product Gas, Hydrogen, kg/h	182.81	118.80	21717.81
CO_2 (plant internal), kg/h	34.80	0.00	0.00
Carbon Black, kg/h	523.60	33.00	17278.80
Water, kg/h	243.50	0.00	0.00
Carbon Char, kg/h	100.00	17.55	1755.00
Pyrolysis Oil, kg/h*	70.00	38.00	2660.00
Heat Losses (kWh)	NA	NA	TBC
Total Energy Out, MJ/h			**41238.8**
Out-In, MJ/h			**-953.26**

2.3. CARBON LIFE CYCLE ASSESSMENT

A carbon life cycle assessment of the Pure Pyrolysis Refined Project has been performed by an external body, ARUP, to evaluate the environmental impacts of the products produced and each of the processes in the proposed configuration.

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. Emissions captured and sequestered in the form of Carbon Char and Carbon Black generated from the pyrolyser and the plasma torch.

The maximum installed load of the process equipment was taken to be 2446 kWe, provided by EPi based on a combination of actual plant data and simulation results, and a 75% utilisation factor.

Grid carbon intensity is taken from the HM Treasury Green Book Data 2022 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.

Table 6 Carbon flow rate at each stage of process

Process Stage	Carbon Mass Flow

Input	0.716 tonnes/hr carbon is input to the system with the SRF.
Stage 1 - Pyrolysis	0.527 tonnes/hr remains in the syngas and 0.051 tonnes/hr is captured in the Carbon Char.
Stage 2 - CO_2 Stripping & Recovery	The syngas after the CO_2 Stripping & Recovery Phase has a carbon content 0.508 tonnes/hr.
Stage 3 - Catalytic MR / WGS	The syngas entering the PT has a carbon content of 0.521 tonnes/hr.
Stage 4 - Plasma Torch	0.521 tonnes/hr carbon is captured in Carbon Black.

Table 7 shows the carbon mass flow rates at each stage of the pure pyrolysis process. Table 8 and Figure 5 demonstrate the carbon dioxide emissions emitted or captured and sequestered at each stage of the pure pyrolysis process. A small proportion of carbon dioxide is emitted in the carbon purge after the CO_2 Stripping phase while the remainder is sequestered in the Carbon Char and Carbon Black.

Table 7 Carbon dioxide emissions at each stage of process

Process Stage	Carbon Dioxide Emissions
Stage 1 - Pyrolysis	0.071 tonnes/hr of **biogenic** CO_2 and 0.115 tonnes/hr of **non-biogenic** CO_2 is captured in the Carbon Char.
Stage 2 - CO_2 Stripping & Recovery	0.013 tonnes/hr of **biogenic** CO_2 and 0.022 tonnes/hr of **non-biogenic** CO_2 is released in the CO_2 purge. The remaining carbon dioxide is fed to the catalytic methanation.
Stage 3 - Catalytic Methanation / WGS Reactor	No emissions at this stage – Carbon dioxide is recycled to the CO_2 Stripping & Recovery Plant
Stage 4 - Plasma Torch	0.725 tonnes/hr of **biogenic** CO_2 and 1.183 tonnes/hr **non-biogenic** CO_2 is captured as Carbon Black.
Parasitic Energy	0.022 tonnes/hr of CO_2 is associated with grid electricity use to power the system.

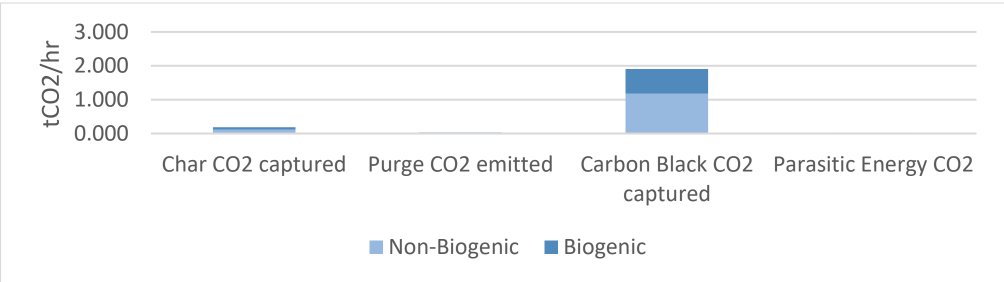

Figure 4 Carbon emissions from pure pyrolysis process

Table 9 below 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 8.

Table 8 Total system carbon emissions

	Description	Value
Total emitted non-biogenic CO_2	*Purged CO_2 (non-biogenic only) + grid emissions*	0.043 tonnes/hr
Total emitted biogenic CO_2*	*Purged CO_2 (biogenic only)*	0.013 tonnes/hr
Total sequestered non-biogenic CO_2	*Carbon Char + Carbon Black CO_2 (non-biogenic only)*	1.298 tonnes/hr
Total sequestered biogenic CO_2**	*Carbon Char + Carbon Black CO_2 (biogenic only)*	0.795 tonnes/hr
Net CO_2 emissions	*Total emitted non-biogenic CO_2 - Total captured biogenic CO_2*	-0.752 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 captured in Carbon Black and Carbon Char has been sequestered by organic material during its lifecycle. By this definition, capturing the biogenic carbon then sequestering in either Carbon Char or Carbon Black can be reported as a negative emission.

Figure 6 below presents the net emissions from the pure pyrolysis process configuration. The results of the carbon assessment show that the process is found to release 0.057 tonnes/hr of carbon dioxide emissions to atmosphere, of which 0.013 tonnes/hour is biogenic and can be treated as neutral, resulting in **0.043 tonnes/hr carbon dioxide emissions to atmosphere**. The process captures a total 2.093 tonnes/hr of carbon dioxide in Carbon Char and Carbon Black, of which 0.795 tonnes/hr is biogenic and therefore can be treated as negative. Therefore, by this rationale, the process results in **0.752 tonnes/hour net negative emissions**.

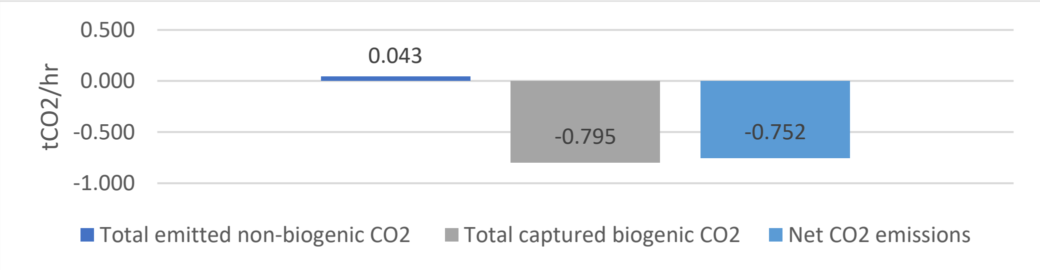

Figure 5 Net emissions from pure pyrolysis process

The detailed calculations have been presented in Figure A2 in Appendix 2.

3. DEMONSTRATION PLANT

3.1. ENGINEERING DESIGN

Simulation studies and pilot plant trials added significant value to the project, to define, layout and mature the concept. Various exercises were performed combined with a series of simulation studies to reduce the complexity of the system, resulting in the creation of the final version of the design, that meets the project requirements effectively. As described in Section 2, fifteen different configurations were designed and studied with the aid of simulations run on gPROMS™ computer model to determine the best possible configuration that can produce highest yields of hydrogen while minimising carbon emissions and maximising the amount of carbon captured. The final design is composed of the following processes: High Temperature Pyrolysis Unit, CO_2 Stripping & Recovery, WGS Reactors, Catalytic Methanation Reactor, Membrane Filters and High Temperature Plasma Torch.

3.2. PROJECT PLAN

Delivery of the project has been split into five work packages as below:

- Work package 1: Completion of the detailed design.
- Work package 2: Procurement and manufacture including FATs and deliveries.
- Work package 3: Civil works of the plant including building.
- Work package 4: Mechanical and electrical installation including RAMS.
- Work package 5: Cold and hot commissioning (functional testing) and process testing (performance and reliability tests).

A detailed testing plan for Functional Testing, Performance Testing for 8 weeks of continuous operation and Reliability Testing via means of repeated functional testing, including the quality testing plan have been presented in Report 9 previously (please refer to Tables A1-A3 in Appendix 3 for the testing plan). The proposed configuration has a number of products, outputs and inputs which require testing and analyses. The results of the tests will be compared with the standards and requirements of the internal and external customers. Every process will be the customer of the previous process that supplies input to that process. Quality and testing model strategy is applied to enhance the successful achievement of strategic business goals as presented in Report 9.

A detailed FMEA will be prepared to ensure a structured approach to identify the ways in which the process or products can fail and estimate the possible risks associated with the different failure causes and evaluate design validation plan in order to reduce the risk of failure. (Please refer to FMEA document (Table A4) in Appendix 3).

In process development and deployment, the greatest risk is often that the product characteristics and yields measured on lab-scale plant will not be representative of "real world" applications when replicated on commercial size plant. These differences can be due to the heterogenous character of the feedstock or simply the effect of scaling up plant and processes from lab scale to full operational size. It must be highlighted that the EPi Pyrolysis technology has already been used at full scale for the production of syngas and electricity from variety of wastes, over a period of 24 years. The EPi plant is now to be combined with a number of complementary technologies and although this final configuration has not yet been tested at scale, all of the ancillary processes are "real world" proven technologies, with many years of operational experience at full scale. Detailed modelling exercises using one of the foremost gPROMS™ computer modelling software, has confirmed that the manner of operation and methods of control are substantially improved in the simulation and FMEA studies undertaken by the project team. However, we fully recognise that identification of the operating conditions required to deliver optimal performance at each step of the process, will need to be undertaken on the full size plant, in order to produce the highest standard of outputs, at the highest levels of efficiency. This phase will be undertaken as part of our optimisation program during Phase 2.

3.3. BENEFITS OF THE PROJECT

This project will significantly advance the introduction of hydrogen production technologies through the development of new technical knowledge and experience on the design and operation of direct carbon capture and other greenhouse gas removal technologies. The system configured will provide a showcase for stakeholders, suppliers, and competitors in this field by providing an example for production of hydrogen with negative carbon emissions that contributes to meeting net zero objectives. The Project will provide a negative emission, cost-effective demonstration of a technology which will provide a substantial contribution to the UK's climate change commitments and targets.

The most essential benefits of the project based on a single module demonstration plant can be summarised as the following :

- The EPi Integrated Technology Solution is extremely flexible, processing a wide variety of feedstocks and capable of running on significantly higher or lower biogenic content feedstock.
- 7,800 tonnes / year feedstock will be converted into energy and valuable products from a single module installation.
- 1,426 tonnes / year hydrogen production, based on the mix of feedstock used in these trials.
- 4,080 tonnes / year Carbon Black will be produced and exploited as a commercial product.
- 780 tonnes / year Carbon Char will be produced and exploited as a commercial product.
- 0.752 tonnes / hour net negative emissions.
- The project results in saving of greenhouse gases from CO_2 emissions to atmosphere by the displacement of wastes to hydrogen.
- The EPi Integrated Technology Solution produces substantial quantities of Hydrogen whilst offering further revenue streams from an additional range of by-products (including Carbon Char, Carbon Black, Centrifuge Cake and Heat Energy).
- Our project can play an important role in helping the UK meet its zero net commitment.
- EPi Ltd will support knowledge dissemination through its upcoming publications. EPi Ltd and Imperial College are currently working to publish their first report on a technical journal.

4. COMMERCIALISATION AND BUSINESS PLAN

4.1. Pure Pyrolysis Integrated Design

4.1.1. EPi High Temperature Pyrolysis Unit

EPi benefits from long established commercial relationships with its existing manufacturing partners and wider supply chain, having worked extensively with each of these suppliers over many years, to deliver each new generation of the EPi technology.

Our key manufacturing partners are licensed by EPi to produce plant and materials to EPi's design and specification with all proprietary components supplied to our partners by EPi. This ensures that EPi maintains over-riding control of product quality, specification and subsequent warranty and servicing.

EPi has also enjoyed long term relationships with our internationally recognised delivery partners who form an integral part of our roll out and ongoing support infrastructure. Bilfinger (UK) Ltd are our appointed delivery partners, responsible for installation and commissioning of the EPi technology onto our designated sites. A well-established and internationally respected engineering specialist, Bilfinger also bring full facilities management in the form of O&M contracts to our client base, wherever required.

The EPi technology offering is further enhanced by our close working relationship with Siemens. All EPi installations will be supported by Siemens, offering a 24/7 responsive engineering support covering all aspects of site operations. Siemens will work with EPi to establish and operate a centralised 24/7 monitoring facility, tied into our existing telemetry and process interface systems. Siemens engineers will also provide responsive maintenance support 24/7 to all operational EPi sites.

4.1.2. Ancillary Process Plant

As an integral part of our configuration to enhance production of Hydrogen, we have introduced a range of existing, proven technologies, already used in various parts of the world to condition the EPi gas outputs for the final plasma phase. Most of these processes are currently deployed at substantial scale and are not generally available at a scale or efficiency suited to the new EPi configuration. In conjunction with our specialist engineering and design partners, EPi have already undertaken some of the preliminary design work in preparation for the production of appropriately sized variants of these ancillary processes, more suited to our intended scale of deployment. For our initial production runs we will utilise the analytical modelling and simulation capabilities of our specialist partners to optimise process design and performance to match outputs to our specific requirements.

4.2. Input Feedstock

The EPi core system is extremely flexible, in that it can process almost any type of waste material. The environmental challenge for removal, diversion or re-use of waste plastics, is an area desperately seeking viable and beneficial solutions on a global scale. The ability of the EPi technology to efficiently process a wide range of waste materials, means that almost any mix of waste plastics could be used in combination with a biogenic feed material, in order to produce a feedstock suitable for our process. The scale of the plastic waste arisings in the UK alone, is currently estimated as ranging between 3.1m tonnes to approximately 5.2 million tonnes of plastic waste per annum. UK Gov data suggests 46% of this plastic is currently incinerated, 19% exported, 17% landfilled with the remaining 18% recycled [1].

For our trials the feedstock was sourced from a London based company specialising in construction and demolition waste (C&D Waste Arisings). There are many such companies around the UK. These operations stream materials collected from skips and sort these into two primary streams; aggregate materials which are cleaned and crushed for re-use within the construction sector, leaving behind a

[1] UK statistics on waste - GOV.UK (www.gov.uk)

balance of material that is mainly mixed waste (paper, card, wood and other cellulosic based material).
Analysis of this material showed a biogenic content in excess of 85%. There are substantial quantities of these materials readily available to mix with HDPE or other types of waste plastic, in order to achieve the required mix of material to suit our requirements for maximising production of Hydrogen.

This principle of adding plastic to a waste material stream can be applied to almost every type of waste stream in both the UK and the wider global markets. Some waste streams will be almost wholly biogenic, whilst others such as domestic or mixed commercial waste arisings, will use substantially less plastic, as these streams already carry higher levels of plastic as an integral part of the waste mix.

Currently, UK local authorities are encouraged to try to sort differing types of plastic for recycling, but this is both time consuming and costly; and not always successful. Worse still, the recovered recycled plastic is frequently at the mercy of market changes; meaning that there will be times when the cost of recovery is not even partially covered by any income produced from the material recovered. Separate streamed collections also bring additional cost to local authorities and cause a reduction in services to the rate payer. A direct consequence of bi-weekly collection services for each individual waste stream.

The wider use of waste for production of Hydrogen and other forms of energy, can bring a wide range of environmental and health benefits, whilst simultaneously reducing costs and improving services to the local rate-payer.

Processing waste streams of all types from various operations within the waste sector, creates an additional income to our operations in the form of a gate fee. Using relatively conservative values, our financial modelling has demonstrated that the levelised cost of Hydrogen can benefit from these other sources of income, created as part of the wider EPi business model.

4.3. Outputs - Residual Products

4.3.1. Carbon Char

There are a wide range of opportunities for generation of additional income by utilising the Carbon Char produced from the feedstock as the Char is predominantly produced from the Biogenic fraction of the feed material. The market value of the Carbon Char can vary substantially dependent upon application, with a typical range between £90 - £300 per tonne. Some examples of applications for the Carbon Char are described in more detail below :

Soil Improver: Intensive farming activities on agricultural land in both the UK and Europe over the last two decades has led to our soils suffering from depleted levels of hydrocarbons. This is a major concern to the farming community. Carbon Char can help to reverse this trend and help to bring about much needed regeneration of the hydrocarbons. EPi has in the past worked closely with the UK Biochar Initiative and academics based at Newcastle and Edinburgh Universities.

The porous nature of the Carbon Char also enables the char to act as a carrier for all manner of fertilisers, soil stabilisers, nutrients, or beneficial microbial strains. The key point here is that using the Carbon Char in this manner, simultaneously achieves carbon sequestration in a single step.

Remediation of Contaminated Soils: The ability to use the Carbon Char as a carrier also opens up opportunities for treatment of contaminated soils. Microbial strains are engineered specifically to neutralise previously identified types of contaminants with the microbes subsequently infused into the Carbon Char. Much work has been done in this sector over a number of years with excellent results achieved within extremely short periods of time following application / treatment.

Construction Materials / Roads: There is a growing awareness of the benefits associated with Carbon Char being combined with various construction materials. This includes cement, concrete, construction blocks and tarmacadam. Current evidence suggests enhanced performance and longevity as some of the benefits to be derived a result of blending Carbon Char into these materials.

4.3.2. Carbon Black

High quality Carbon Black is a substantially different material from Carbon Char, offering extensive opportunities for a range of specialist applications. Carbon Black is a high value product with a wide range of potential uses in various commercial sectors. As with Carbon Char, values will vary according to final application, with some applications commanding prices of over $2,000 (US) per tonne.

Industrial Materials: Semi-Conductors and Carbon Filters - Nano Carbon Materials for EV market. Our current client base has commercial relationships with manufacturers requiring high quality Carbon Black to be used within a variety of commercial operations. Existing users would greatly improve their carbon footprint by utilising Carbon Black produced from a renewable source, existing production of Carbon Black is an energy intensive process with a high carbon footprint.

Cosmetics: Through our existing commercial client base, we have been recruited by one of the leading international cosmetic brands. Carbon Black has opportunities for a range of applications within the cosmetics industry and trials are currently underway, to develop this opportunity further.

Ink Market: The global shortage of materials following the effects of the pandemic, has placed an additional load on the market of printer / copier ink and the paints industry. This has forced prices ever higher for Carbon Black as a raw material in various sectors. We are excited about the opportunity of promoting this high quality, low carbon, environmentally advantageous Carbon Black into an eager and substantial global market.

4.3.3. Hydrogen

The market for Hydrogen in the UK is in its embryonic stages, but we have already secured a number of outlets for our Hydrogen production, caveated by a requirement to demonstrate predictable and robust supply lines. Applications are currently diverse, but amongst our current client base we have agreements in principle for the following applications.

Agricultural & Marine Fuels: A UK client for supply of Hydrogen to two UK projects. The first of these being an agricultural project requiring stand-alone power hubs and distribution lines for parts of a Hydroponic network. The second project relates to a Tidal Transit link. Our client wishes to convert a fleet of up to 500 small maritime vessels to alternative fuels derived from the EPi process. Zero sulphur, renewable liquid fuels and Hydrogen being their main areas of focus. The primary reason for the mixed requirement, being that not all vessels will convert to hydrogen immediately. It will require a phased approach. A proportion of the vessels will simply run on alternative liquid fuels, which we can also supply, until they are ready for conversion to hydrogen.

Maritime Industry: We are currently working with a UK specialist engineering company, aligned with a major European operator of commercial shipping. They have successfully modified existing marine diesel engines to run on hydrogen. The initial focus on maritime engines is due to the excessive emissions normally associated with marine diesels. Prices have been agreed and our client will provide carbon fibre storage tanks and compressors on our site, located on the back of commercial trailers.

4.4. Site, Licensing and Planning & Permits

Historically, planning applications involving waste treatment have taken years to progress through planning and been the subject of many public meetings and subsequent appeals. Fully justifiable public concern over environmental issues, including emissions, air quality, increased transport volumes etc… have traditionally been the cause of conflict between a concerned public and the necessary requirement for local authorities to find a solution to the treatment and disposal of waste.

The EPi process avoids many of the negative aspects of the established solutions, the plant is low profile and occupies a small footprint. There is no combustion, no airborne emissions and invariably the plant can be located next to the existing waste. In our case - The feedstock.

EPi has been involved in various planning applications over the years at various sites around the UK. With the singular exception of a recent application in Chelmsford, (which suffered delays due to Covid) all other applications were passed in less than 14 weeks from the date of submission.

We are advised that Regulatory Permitting applications for single module plants will be regulated under the Local Authority Environmental Health teams. We are advised to expect durations of 12 - 14 weeks from date of submission.

4.5. Commercial Readiness

We currently have three commercial sites under consideration, one where an option agreement is currently under negotiation. All three sites are either adjacent to existing waste operations of the appropriate scale or can be included on a site that already hosts an existing operational waste plant.

As mentioned earlier in the document, EPi has a single module commercial reference plant currently under manufacture. The timelines presented in earlier parts of this document reflect the current status of this plant.

In essence we are poised ready to add the proposed configuration of ancillary process to the EPi plant already in manufacture, with the consequential saving to this project of the capital cost of the EPi core Pyrolysis technology. Not an inconsequential sum.

The timing for moving forward to Phase 2 is immensely beneficial, from this perspective alone.

5. COST ANALYSIS – NPV & LEVELISED COST OF HYDROGEN

As described in detail in BEIS (2021), 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 this report, the LCOH is calculated by accounting for the NPV of the CAPEX, OPEX, revenues, and the cost of carbon sequestered. 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, while by-products of other technologies need to be disposed of, the Carbon Black and Carbon Char produced in this configuration are commercial products and their disposal route is through sales to a range of end users.

Similarly, raw materials incur costs, however waste as feedstock leads to revenues. Therefore, the associated sales price can be considered as either negative variable fixed cost or positive revenues.

A 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 hurdle rate is applied based on data from BEIS

(2021)[2]. The NPV and the LCOH are demonstrated over three plus 5, 10 and 25 years. The initial period is taken as three years as the full plant with six modules is only commissioned and tested after the first three-year period. Therefore, the calculations are demonstrated as Phase 2 (this is a 2-year period organised by H2BECCS) plus 6, 11 and 26 years. Contribution of cost of all the related items to the LCOH is realised through calculating the NPV and associated levelised costs.

6. CONCLUSIONS

EPi Ltd, in collaboration with its partners provides a unique combination of systems which convert waste into a high calorific value fuel gas and Carbon Char in line with the requirements of H2BECCS programme. This report acts as a summary of the studies performed during the project to achieve the project requirements which is hydrogen production of hydrogen from a biogenic content feedstock (min 25% by CV) with minimum carbon emissions.

The final design is proposed following an extensive literature review, taking into account the results obtained from two-stage lab scale pyrolysis trials as well as 15 different simulations run on gPROMS™ Process 2.2 computerised model. The hydrogen yield reported is also validated on an alternative computerised model, CFD (Computational fluid dynamics computerised model).

The EPi Integrated Technology Solution incorporates the following process phases in order to achieve the highest H_2 yield with the lowest possible CO_2 emissions:

- Pure Pyrolysis
- Gas Cleaning & Conditioning,
- CO_2 Removal & Recovery Phase,
- WGS,
- Methanation Reactor,
- Membrane Filters,
- Plasma Torch.

The integrated process has been configured to maximise hydrogen yield, starting from almost any organic feedstock with the ability to tolerate variations in the input waste material. Our Lab scale trials were conducted on mixtures of SRF, and waste plastics, with simulation results demonstrating that this configuration is capable of converting **1 tonne of waste into 182.8 kg of product gas, 90.13% of which is pure hydrogen amounting to 164.7 kg of hydrogen per hour.** The proposed design provides great potential for Carbon Capture through its by-products including 523.6 kg/hr solid Carbon Black and 100 kg/hr solid Carbon Char and 70 kg/hr oil being the result of EPi's integrated pyrolysis solution, processing 1 tonne/hr of SRF.

The results of the carbon assessment showed that EPi's pure pyrolysis process results in **0.752 tonnes /per hour net negative emissions** meaning that the project effectively achieved meeting the requirements of the programme.

EPi have started negotiations with manufacturers and suppliers appropriate to our needs. Proprietary equipment will be provided via our existing supply chain in order to maintain quality standards throughout the various areas of the plant. A consistency of supply lines leads to continuity of quality and ease of replacement. Our current suppliers of proprietary equipment and instrumentation are predominantly UK based and are well versed in supplying product to our specification and familiar with our needs. The more specialist items of ancillary plant identified by this exercise are currently supplied by large international companies and produced at a scale that is not appropriate for either pilot operation, or indeed our intended scale of deployment. We are currently drawing up manufacturing designs for these items and will shortly be circulating manufacturing specifications to a number of UK manufacturers capable of producing to our requirements.

2 BEIS, (August 2021), "Hydrogen Production Costs 2021", Department of Business, Energy and Industrial Strategy, pp: 25-26

The aim of the Phase 2 project will be accommodating the development and commissioning of a fully integrated pyrolysis system as proposed in Phase 1 and demonstrating successful and continuous operation of the technology in a full-scale commercial context. Phase 2 has been designed for the installation and operation of the project configured in Phase 1 and to test and improve the findings, and assumptions made during this Phase 1 feasibility study. Commercialisation and optimisation studies performed during phase 2 are expected to result in a reduction in cost. Our project will provide an emission free, carbon negative, cost-effective demonstration of a technology which is considered to be of a high level of importance in reaching the UK's climate change commitments and targets.

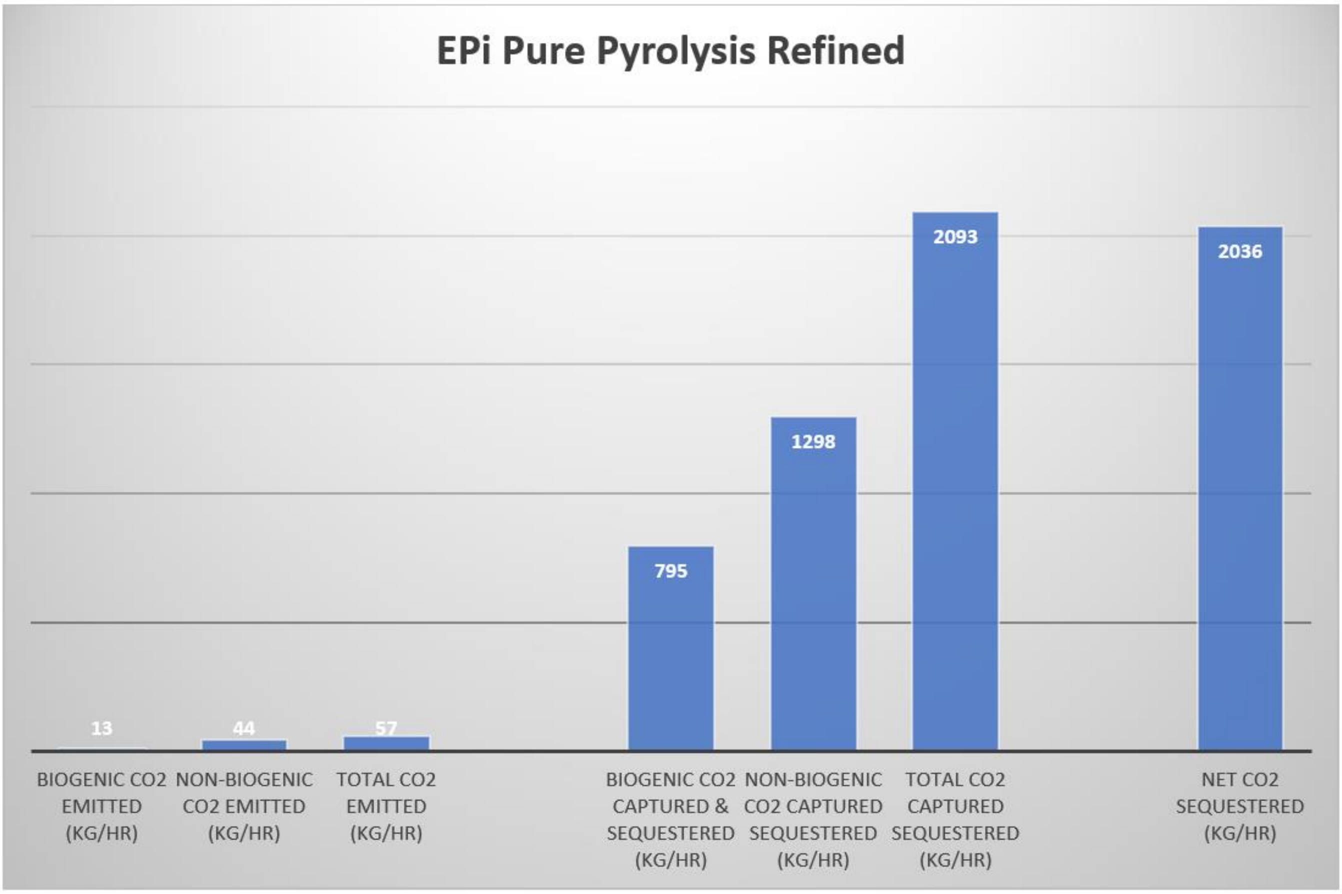

Figure A8: Total CO_2 emissions emitted and sequestered.