Project Final Report – Queen Mary University of London

Hydrogen BECCS Innovation Programme: Phase 1

Novel plasma reforming technology for tars reduction in BECCS

Contents

1 Brief outline of the scope of the project

Low carbon hydrogen will be critical for meeting the UK's legally binding commitment to achieve net zero by 2050, and hydrogen generated via biomass gasification has the potential to deliver negative emissions required to offset emissions from hard to decarbonise sectors. The overarching objective of this project with relation to the Hydrogen BECCS Innovation Programme was to support development of novel technologies that effectively control contaminant concentrations (tars in particular) to improve gasification process performance and reduce levelised cost of hydrogen.

Specifically, this project focussed on assessing the technical, environmental, and economic feasibility of using a novel triboelectric plasma reforming technology to replace the existing thermal plasma gasification technologies based on external sources of plasma energy. As opposed to conventional thermal plasma reforming technologies, which rely heavily on expensive power supply and transmission systems, triboelectric plasma, or "triboplasma", is generated within the reformer process by controlling and exploiting particle collisions and their resulting electrostatic charges. When triboelectric discharges occur in a controlled manner, the highly ionised environment becomes very similar to that generated by conventional thermal arcs.

The application of the technology is focused on the thermochemical conversion of tars and other contaminants from the syngas produced in commercial scale gasification reactors. The project used a combination of computational modelling performed by a team at Queen Mary University of London and small-scale experiments at University College London to develop a fully costed design and delivery programme for a pilot triboelectric reformer reactor that will be installed and thoroughly tested in an existing gasification plant at Cranfield University in Phase 2 of the programme.

2 Technical description of the science and engineering

2.1 Background

The Gasification process converts solid feedstock, such as biomass and waste, into a mixture of hydrogen and carbon oxides, called syngas. This is achieved by reacting the material at high temperatures (>700-800 °C), with a controlled amount of oxygen and/or steam to avoid combustion. The syngas, once cooled and cleaned, can be separated into pure streams of hydrogen and CO2. When the CO2 is stored, the entire process can be considered as "carbon neutral" if all the carbon originates from fossil or mixed feedstock, or even "carbon negative" when a significant proportion (typically over 50% in weight) of biomass is present in the original feedstock. For this reason, gasification is the key underpinning technology of BECCS (Bioenergy with Carbon Capture and Storage), and is therefore a major enabler of the transition towards net zero-carbon economy. Biomass gasification has been encouraged for power and transport applications in UK, however, existing plants still experience severe operational issues (Status report on thermal gasification of biomass and waste 2021 Research special report IEA Bioenergy: Task 33 February 2022). Examples of these have been surveyed by BEIS and reported in their recent report ("Advanced gasification technologies: review and benchmarking"). The syngas produced from gasification of biomass contains not only the useful CO and H2, but depending on operating conditions and gas upgrading methods, varying quantities of undesirable pollutants that require removal such as: tars, heavy hydrocarbons, organic and inorganic sulphur, polycyclic aromatics, HCl and ash particles with metals that may include potassium (causing fouling), lead, and mercury. The key challenge for implementing efficient gasification systems globally is delivering an integrated, engineered system reducing problematic components/pollutants to a manageable level (appropriate for the downstream conversion technology) consistently and cost-effectively.

2.2 Plasma Gasification

Thermal plasma technologies can be used in combination with conventional gasification technologies (e.g. fluidised beds, downdraft, etc.) due to their ability to convert the tars and break-down other contaminants to facilitate removal by well-established processes. This has been demonstrated by several companies, including ABSL, Europlasma, Plasco, etc. Compared to other purely thermal cracking technologies based on flames and oxygen addition (like those used by KEW Energy or Chinook), plasmas show a far greater chemical reactivity and quenching rate. This is due to the high operating temperatures, which exceed those produced under combustion, and the formation of chemically active species (CAS) – free radicals, ions, and excited molecules. As a result, any organic molecules, exposed to the intensive radiation, break-down into simpler elements (e.g., H2, CO, N2, H2S, etc.), with solid inorganic components (glass, metals, silicates) fusing to form a molten slag, which vitrifies on cooling. This is a feature which has been exploited for many decades to make incineration ashes inert or to recover valuable metals in metallurgical industries. In comparison to other refining techniques, including microwave and “cold” plasmas, reforming by thermal plasma exhibits significant advantages, such as large treatment capacity, higher flexibility, and high tars conversion efficiency. Nevertheless, the complexity of the electrical and cooling circuits, the high capital and operating costs of conventional generators, as well as the cost of the maintenance of the refractory lining of the plasma reformer and the frequent replacement of electrodes have encouraged both researchers and industry to consider other sources of electric energy generation.

2.3 Key Innovation

Triboelectricity, or electricity generation by mechanical friction, provides an alternative source for CAS and plasma ion generation, at a much lower cost when compared to direct power systems. An excellent example of triboelectric charging occurs in the plume of volcanic ash clouds during an eruption. Ash particles produced from the eruption collide with one another producing significant charge, which is discharged subsequently through lightning strikes. Many applications currently utilise this effect, e.g. ore separation, and energy harvesting via utilisation of the kinetic energy of a flow of dielectric liquid or gas in the presence of a conductor surface.

In a recent publication (Tsiklauri at al. "The Effect of Particle Gas Composition and Boundary Conditions on Triboplasma Generation: A Computational Study Using the Particle-in-Cell Method." IEEE Transactions On Plasma Science (2020),1-12.), the group at QMUL performed kinetic plasma simulations of an idealised triboplasma reactor, which showed that the presence of small char particles including fullerenes (C60) and the boundary condition of a conducting wall are the key elements required to significantly enhance plasma ionisation. This work provided a theoretical foundation of controlled discharges of triboelectric energy, which were used for the generation of a stable and topologically coherent triboplasma region in the experiments of the inventors of the triboelectric plasma technology, who are partners in this project.

In the existing triboplasma apparatus, thermal plasma is generated from electric discharges resulting from the collision of gas particles with a serrated surface of an insulated steel inductor and is stabilised using a system of non-uniform swirling hydrodynamic flow and electromagnets. The ignition process works virtually as 'lightning in a box'. The high temperature plasma is then used to pyrolyse biomass waste in a closed cycle without the requirement for external power supply associated with plasma generation. The existing apparatus is used primarily to transform waste into burnable gases. However, a similar triboelectric plasma principle can be used potentially to replace the expensive and high-power plasma systems in plasma-assisted gasification systems, whereby plasma is specifically used for tar reforming. The integrated system can produce clean syngas efficiently at lower cost, increasing the benefits of biohydrogen.

2.4 CCS Compatibility

Most commercial catalytic systems and CO2 capture technologies cannot be applied to tar-laden syngas, due to high risks of blockage, catalyst/solvent contamination and vessels/piping fouling. The current innovation is aimed at producing a syngas free of tars and other long-chain hydrocarbons, suitable for cleaning in conventional dry/wet scrubbers, prior water gas shift and CO2 separation. It is therefore fully compatible with conventional pre-combustion CCS plants. Furthermore, the very low parasitic load associated with plasma generation (compared to other plasma reforming technologies) enhances the carbon benefit of the process.

2.5 Technology Development Status

2.5.1 Triboplasma technology

In comparison with traditional plasma gasification or plasma reforming reactors, which are based on the principle of generating steady plasma zones such as corona or thermal arc discharge, the triboelectric plasma is pulsating and intermittent by nature. This non-stationarity is caused by individual collisions of multiple charged gas particles with the isolated parts of the reformer reactor, which accumulate the charge of an opposite sign compared to the colliding particles due to the triboelectric effect.

2.5.2 Summary of the work done during the Phase 1 project

The Phase 1 project has focused on the development a proof-of-concept computational model of the reformer reactor corresponding to the plasma stage of the two-stage gasification process. The model has been used to optimise the design of the inlet pipes to enhance the formation of the triboelectric particle zone in the centre of the reformer reactor. The upstream syngas condition of the pilot triboplasma reformer model has been tailored to mimic conditions of the hosting gasification facility at Cranfield, which will be used in Phase 2. At the same time, the size of the reformer model has been selected to match the typical gas residence time of reformer reactors used by the potential industrial partners/customers of the suggested technology. In parallel with the computational modelling, a series of small-scale pulsating plasma experiments have been performed (at UCL) to inform the modelling and establish confidence that a non-constant plasma source can be used for tar reforming.

2.6 Computational Model

A range of Computational Fluid Dynamics (CFD) models of the reformer chamber design to be used in Phase 2 of varying fidelity have been developed – from single phase to multicomponent reacting flow. The key effect the models were required to simulate is the formation of the uniformly swirling flow around a central element of the reactor, the so-called inductor, which is the key attribute that enhances the triboelectric particle collisions. An optimal design of inductor was suggested after a discussion with the triboelectric plasma expert. The inductor was placed in a cylindrical reformer vessel with several inlet and outlet pipes to generate the recirculation flow in the centre. The location of the inlet/outlet pipes in the reformer vessel suggested by the triboelectric plasma expert was refined after a series of CFD calculations.

Before being applied to the Phase 2 project geometry, the CFD models were validated on several benchmark cases from the literature such as the modelling of cyclonic flows and non-thermal arc plasma torch for diesel fuel reforming. This benchmarking work enabled a high level of confidence to be obtained in the computational modelling capability, including the choice of CFD grids, turbulence models, and the libraries of chemical reactions.

All calculations were performed with the Star CCM+ solver on an HPC (High Performance Computing) cluster in QMUL using the existing computer licenses and computing resource allocation.

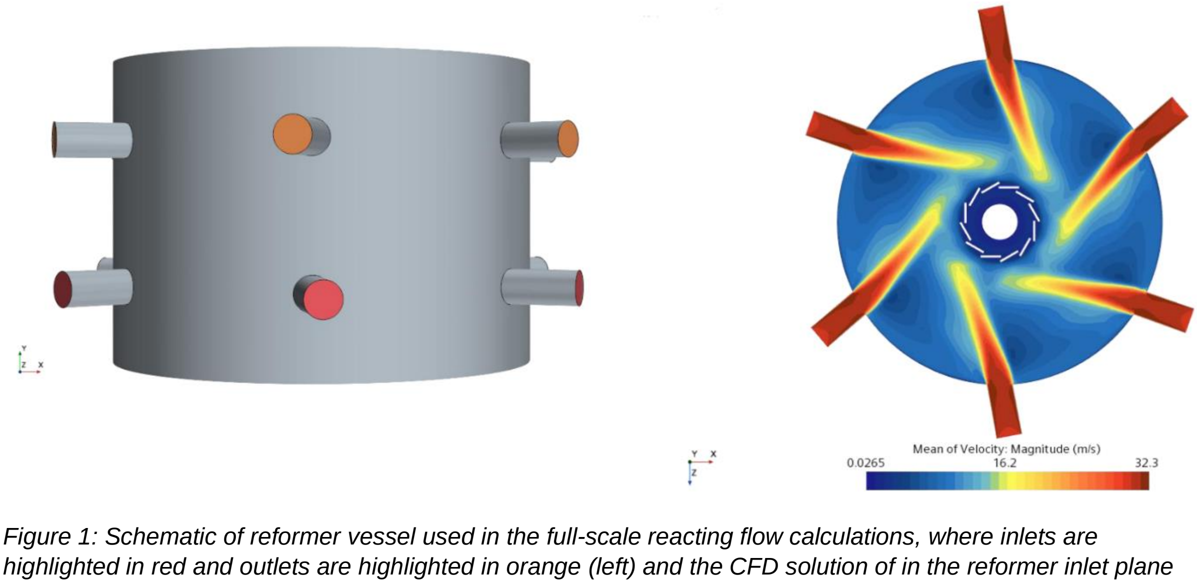

Figure 1: Schematic of reformer vessel used in the full-scale reacting flow calculations, where inlets are highlighted in red and outlets are highlighted in orange (left) and the CFD solution of in the reformer inlet plane coloured by mean velocity magnitude (right).

The CFD simulation requires information on the triboelectric particle charging process in order to define the triboelectric plasma source region. The triboelectric charging was semi-empirically defined by extending the existing triboelectric models available in the literature. The objective of the semi-empirical modelling was to predict the charge distribution on the gas particles at exit from the recirculating pipes connected to the reactor vessel. Results from the model were used also to evaluate the level of particle charging due to the interaction with the inductor in the centre of the reactor vessel.

The analytical particle charge model considers a fully developed flow of multi-component gas corresponding to the main chemical species present in typical syngas generated in fluidised bed gasifiers, as informed by UCL team (M Materazzi, P Lettieri, Fluidized beds for the thermochemical processing of waste, Elsevier, 2017). Differential equations with respect to the radial coordinate are used to characterise the variation of particle velocities, their concentration, and charge distribution with an accounting for collisions and diffusion across the flow. Empirical work functions are used to model the triboelectric particle-particle and grazing particle-wall collisions. Governing equations of the model were solved using numerical solvers in Matlab combined with analytic solutions and provided several insights into the particle charging process to inform the CFD simulations.

Finally, by combining CFD with the thriboelectric charge modelling, a 3D reacting flow model was developed for plasma-assisted reforming, and calculations were performed on the full-scale reformer geometry to investigate the effects of the triboplasma power source on reforming of tars in syngas using a combustion mechanism. The location of the tribo-plasma volume source takes the form of a three-dimensional toroid, and this was determined by the results from a Lagrangian multiphase particle tracking simulation. Particles were tracked from the inlet and considered charged after colliding with the inductor. A large concentration of these particles is deflected upwards into the region above the inductor which forms the toroid. The intensity of the volume source was estimated using an order-of-magnitude analysis based on the results of the triboelectric charging modelling and the existing experimental data. The results from the calculations indicate that the presence of a power source from triboplasma will not only result in the reforming of tars but also contribute to increased production of hydrogen within the reformer (Fig.2). The utility of the model applies directly to informing the design and development of future triboplasma reformers.

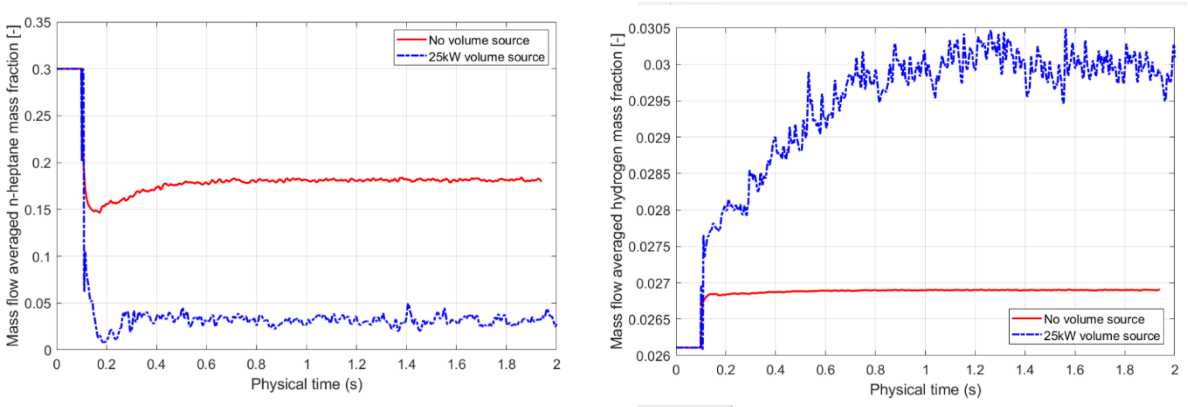

Figure 2: The distribution of key mass flow averaged quantities across all syngas flow outlets with and without the triboplasma volume source: n-heptane mass fraction, which represented tars in the simulation (left) and hydrogen mass fraction (right).

Although highly simplified in its current state, the approach to modelling is intended to be developed and refined to include the effects of plasma chemistry and undergo further stages of validation. Furthermore, a more complete simulation model would need to include a more accurate calculation of the triboplasma source power by simulating individual gas breakdown discharges at the microscopic level and extrapolating the results to the toroid triboplasma volume. Such a calculation will be important for the accurate evaluation of the energy balance of the suggested technology to answer the question how the current design can be scaled up from the demonstration scale to the commercial gasifier scale. Ultimately, the computational model will be a key component of future development of triboplasma technology and can contribute greatly to reducing the costs of prototypes while aiding the development of the Phase 2 design and commercialisation in the years ahead.

Despite the modelling limitations mentioned, the current computational model already provides sufficient technical certainty that the suggested reformer design will generate the desired swirling flow of particles, whose triboelectric energy could be sufficient to contribute to tar reduction and increased production of hydrogen.

Detailed results of the computational and analytical modelling are provided as an annex to this report.

2.7 Pulsating Plasma Experiments

The UCL pulsating plasma reactor was set up for the requirements of the project. The reactor has a cylindrical geometry typical of industrial plasma furnaces. The reactor is instrumented to be supplied with a variety of simple hydrocarbons at the inlet to simulate tar-laden syngas and is connected to a suite of analytical equipment to fully characterise the product syngas and the residual tars downstream of the reactor.

The plasma is initiated by a high voltage power supply, in the form of short (~10–100 ns), high current (~1–10 A) pulses. In this way, it is possible to prevent the thermalization of the plasma during the spark phase, simulating the reacting behaviour in triboelectric regions. A simulated tar component (n-dodecane) was injected through the localised plasma region, to study its evolution, in inert gas, or simulated syngas (H2, CO, CO2). An online IR camera also provided details on temperature distribution around the discharge point. The objective was to understand the capability of the system to reform tars at temperature (~700-800 C) significantly below those typically encountered in plasma reforming (1,200-1,300 C). For the tests, n-dodecane was selected as the tar analogue compound, due to its simple structure, relatively high thermal stability and low boiling point.

The main aims of this work have been:

1.To investigate the feasibility of treating tar hydrocarbons with pulsating plasmas at reduced temperatures (~700-800 °C) and with no oxygen addition;

2.To investigate the applications of discontinuous thermal plasma electric discharge reactor for a tar simulant component (n-dodecane) using conditions similar to those that would be encountered in the triboelectric reformer for Phase 2.

The performed tests have shown that tar reforming in the syngas is possible even at discontinuous discharge conditions and reduced temperatures (see Figure 3). In particular, it was observed that when n-dodecane in injected into the system (15:15), a stepwise increase in H2, CH4 and CO was observed, together with a significant decrease of CO2.

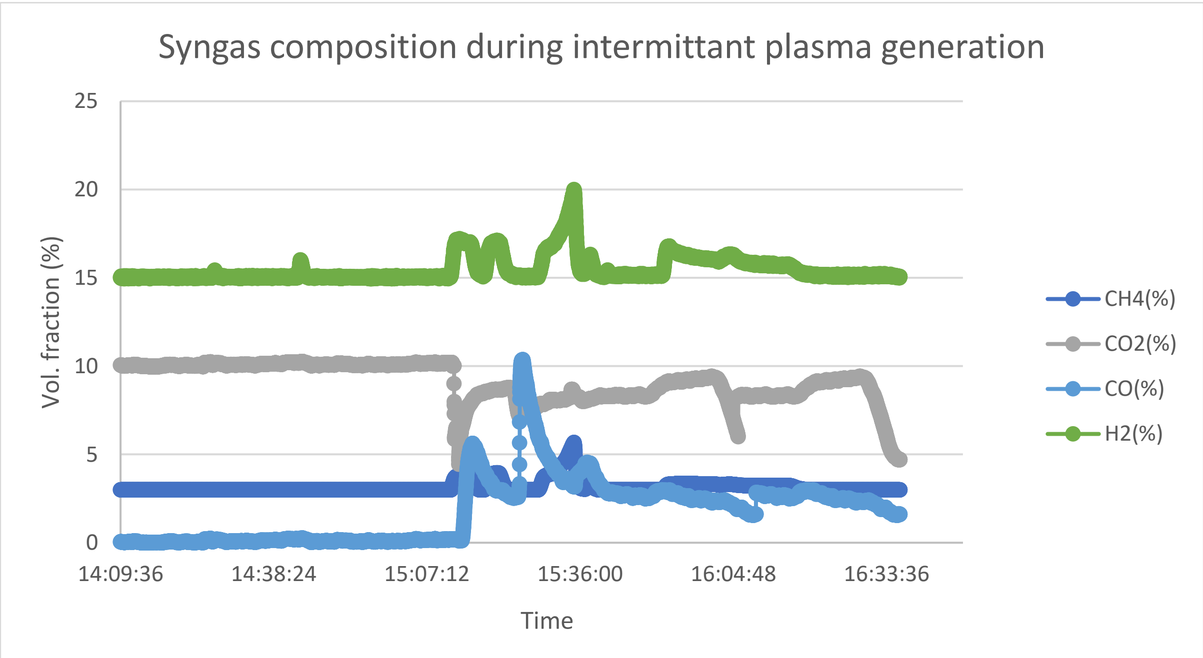

Figure 3: Syngas analysis from tests at UCL, in which a gas mixture of H2, CO2, Steam, CH4 and vaporised C12 hydrocarbons are exposed to intermittent plasma discharges

This is due to the combination of CAS species generated by the plasma from oxygen-containing molecules, such as steam and CO2 already present in the syngas. While the level of conversion observed for one pulsating plasma source at the considered operating conditions was not deemed sufficient for industrial applications, multiple pulsating plasma sources such as those generated by triboelectric discharges would entail a much larger reforming zone which would ensure a higher potential for tar reforming.

Further results of the experimental investigations are provided as an annex to the report.

3 Carbon life cycle assessment

A preliminary Life Cycle Assessment has been undertaken at UCL to understand the climate change impact of a triboelectric plasma reformer in a H2BECCS plant. The full mass and energy balance was prepared for a commercial scale bio-H2 plant (66MWth input) using plasma reforming and treating waste feedstock, published already by UCL team [Amaya-Santos et al., Biohydrogen: A life cycle assessment and comparison with alternative low-carbon production routes in UK, Journal of Cleaner Production, Volume 319, 2021], as part of a previous project. The chosen functional unit of this study was the production $1MW_{HHV}$ of BioH2 (>99.97% purity) from waste feedstock. The model was modified to take into account the different energy (electricity) input in the reforming stage, due to the different discharge mode of the plasma reformer in the two cases. The different plasma generation process leads to a reduction in energy consumption of approximately 90% for the plasma converter stage only, corresponding to less than 8% reduction for the entire plant and a total plant carbon footprint of 36 kg CO2eq./MW of hydrogen produced (Fig.4, left).

For indicative purposes, the environmental performance of the triboelectric refined Bio-H2 technology was compared also to two other competitive low-carbon technologies, namely Blue H2 via autothermal reforming (ATR) and steam methane reforming (SMR), and Green H2, with electricity sourced from the current grid (as in 2020), 100% offshore wind, 100% solar, or ~74%/26% mix of the two (see Figure 4, right). The comparison of the environmental performance of the three routes has been performed taking into account the environmental burdens allocated solely to the production of hydrogen. The emissions displayed for Bio-H2 and Blue-H2 are referred to processes that also include CCS (90% carbon capture rate).

Blue-H2 produced via ATR or SMR with CCS process produces 56.6 and 63.2 kg CO2 eq. per MWHHV transport grade H2, respectively.

A competitive Green-H2 route of production is limited by the high electricity demand of the electrolyser. This is evident when operating an electrolyser using the current UK electricity grid mix leading to a marked environmental underperformance, with a climate change impact of 374 kg of CO2 eq. per MWHHV H2. This limitation can be overcome by using exclusively renewable electricity, as shown in Fig. 4, right.

Bio-H2 production shows the lowest contribution to climate change, equating to -176 kg CO2 eq. These results show that the production of hydrogen from MSW together with the sequestration of carbon, is not only an effective solution to waste disposal, but it is also appropriate to achieve the objectives proposed by the Net Zero 2050; its implementation involves the removal of nearly a quarter ton of CO2 per MWHHV of H2 produced every hour.

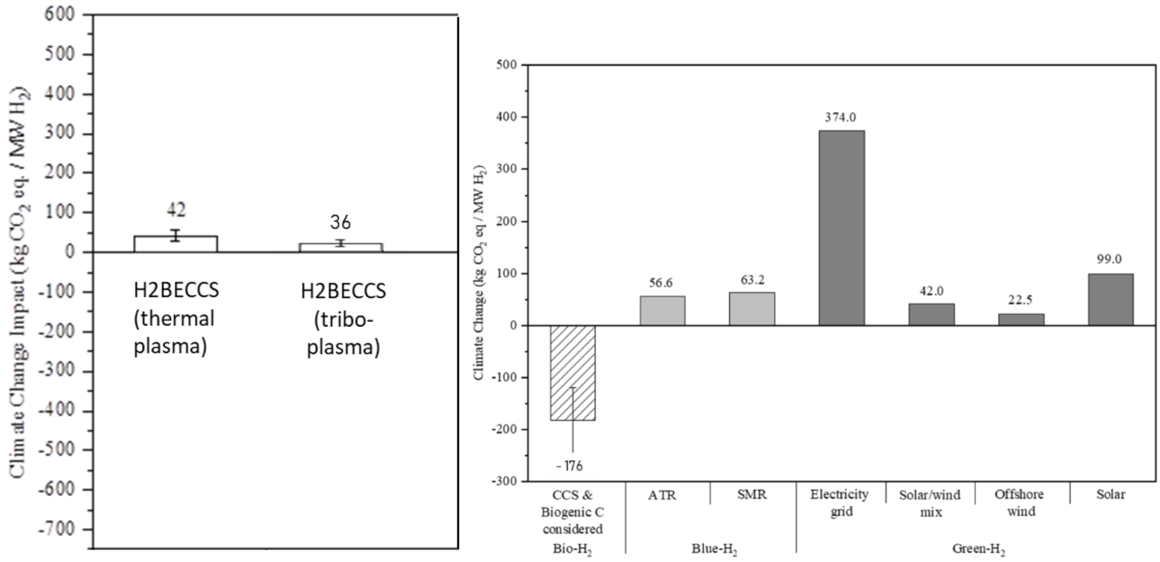

Figure 4. Climate change impact (CO2 eq. per FU) regarding carbon capture and storage (no carbon credits for CCS have been considered). Uncertainties calculated based on waste composition and technical variations in energy usage (left). Climate Change contribution comparison of Bio-H2, Blue-H2 and Green-H2 production technologies. Uncertainties calculated based on waste composition (40-60% biogenic C variation) and technical variations in energy usage.(right).

The evolving pertinence of these technologies within the energy transition landscape is an important consideration as LCA results are strongly affected by the energy supply, particularly electricity. Hence, a scenario analysis was conducted to compare the environmental burden due to climate change of each hydrogen production route according to the electricity mix predicted for the UK in 2030 and 2050. Bio-H2 production impact contribution decreases by 25% in 2030 to -235 kg CO2 eq. and by 56% in 2050 to -248 kg CO2 eq., relative to the present-day case. This is due mostly to the reduction in electricity cost (in terms of carbon footprint) associated to use of pumps, compressors and electric heaters. With this assumption, all H2BECCS processes (with conventional and triboelectric plasma) technologies will have a very similar impact in the future, and the benefits of triboelectric reforming on carbon impact will become less important.

In comparison, Blue-H2 production via SMR and ATR has a smaller differentiation in climate change as the grid moves to decarbonisation. This is due to its lower overall electricity consumption. In addition, a large part of its contribution is dominated by upstream feedstock emissions and CO2 process stream emissions and thus comparatively unaffected by changing electricity mix.

Further details of the Life Cycle Assessment are provided as an annex to this report.

4 Engineering design for a demonstration project

The cylindrical reformer vessel consists of two casings, internal and external separated by a gap, which can be filled in by a foam. The internal casing is made of a refractory/ceramic material and is electrically isolated from the ground. The external casing is made from a stainless steel metal and is grounded. In the centre of the reformer there is an electrically isolated inductor, which is important for triboelectricity generation. The inductor is manufactured from an alloy, which has similar triboelectric properties to a stainless-steel metal and can withstand high temperatures, such as Inconel. It will accumulate the electric charge of an opposite sign compared to the particles.

A separate fan-driven pipework contour, which is divided into 6 inlets/ outlets at the entrance to the vessel, is used, which is made of a stainless steel metal. This pipework provides particle gas streams which impinge tangentially on the inductor surface and generate a swirling flow in the centre of the reformer volume. The particles exiting from the 6 inlets are charged due to the interaction with the pipe wall. The speed of the 6 inlet jets (~ 20-30m/s) is controlled by a recirculation fan which is sufficiently cooled to withstand the gas temperature, whilst avoiding the condensation of tars, following recommendations of the triboplasma expert.

The solid feedstock feeding of the Cranfield reactor is estimated to be of a mass flow rate at 10kg/hr. This correspond to approximately 15kg/h of produced syngas which is directed to the new triboelectric reformer. To simplify the control of the inflow speed/ flow rates of the recirculating streams higher than 15kg/hr, two additional inlet/outlet are included, below (inlet) and above (outlet) the 6x2=12 streams. The inlet streams will carry syngas at ~ 800C of a specified chemical composition.

In addition to 6x2 + 2 apertures for the recirculation pipes and syngas inlet/outlet, a number of side rectangular apertures are needed. One is to install a window made of a heat resistant glass for optical measurements of the triboplasma in the vicinity of the top part of the inductor. The others are technical hatches to collect the ashes and solid residuals. Another option for the same would be to include a hatch at the bottom of the reactor vessel.

The suggested size of the reformer vessel diameter was selected to match the residence time of gas phase in the reformer prototype used by our potential industrial customers.

Detailed sketches of the reformer are provided as an annex to this report.

5 Approach to testing the innovation during the Phase 2 demonstration project

Phase 2 of the project will focus on testing of the developed plasma reformer design in the existing gasification plant in Cranfield.

The key performance indices to be examined will be tar conversion efficiency, H_2:CO ratio at the inlet and outlet of the reformer, and fly ash removal efficiency compared to conventional plasma reformers.

The key areas for testing are the following:

a) Performance: The high temperature necessary for tar conversion to syngas is generated in the reaction zone due to the triboplasma effect - without a constant additional input of oxygen or external plasma sources.
b) Quality: The end product – syngas, is delivered to the quality criteria required for use and downstream processing to hydrogen in accordance with the IGEM Hydrogen Gas Quality Specification[1].
c) Assessment of the environmental compliance of the emissions.

Testing will consist of a short functional test and long-duration performance/reliability test. Functional testing will be conducted before and after the long duration performance testing to also determine whether these is any deterioration in performance over the performance period. Performance testing will be performed for a minimum of 1,000 hours cumulatively (or more, if required).

During the testing period the following data will be collated:

a) Operating Hours

b) Downtime due to planned maintenance

c) Downtime due to unplanned maintenance

d) Equipment and / or component failures, including root cause analysis

e) Gas leaks

f) Consumables used such as oils and greases

g) Energy consumed

h) Water consumed

i) Daily log of activities such as:
    i. throughput of syngas
    ii. quality and volume of the cleaned syngas output
    iii. adjustments to operations and staff
    iv. influencing factors

The results from the testing will inform key decisions for commercial scale-up of the technology such as material selection, mitigations for identified issues, practicality of commercial operation, operating condition optimisation as well as further recommendations for the design improvement such as the location of technical hatches for the removal of ashes and solid residues.

[1] https://www.igem.org.uk/technical-services/technical-gas-standards/hydrogen/igem-h-1-reference-standard-for-low-pressure-hydrogen-utilisation/ (Appendix 4: HYDROGEN GAS QUALITY SPECIFICATION)

6 Detailed and costed project plan

6.1 Timelines for deliverables

Month	1-6	7-12	13-18	19-23
WP1				
WP2				
WP3				
WP4				
WP5				
WP6				
WP7				
Milestones		**MS1**	**MS2**	**MS3**

Work Packages (WP):

WP1. Detailed engineering drawings, procurement with constructors, manufacturing and construction of the reformer, Month 1 - 9

WP2. Installation and commissioning, Month 10-12

WP3. Operation and testing, Month 13-22

WP4. Computational modelling to help optimising the operational regime of the prototype reformer, Month 1-15

WP5. Computational modelling to evaluate the effect of scaling up the prototype reformer to a commercial reactor size, Month16-22

WP6. Marketing and spinout activities, Month 17-23

WP7. Preparation of the final report, Month 22-23

Milestones (MS):

MS1 The reformer reactor is built

MS2 The operational regime is confirmed

MS3 The testing programme is completed

6.2 Project management (including project team and key suppliers)

The project team will include:

Personnel	**Responsibilities and Expertise**
Sergey Karabasov (QMUL)	Project coordinator, QMUL team lead, and computational modelling authority
Nader Karimi (QMUL)	Chemically reacting flow modelling authority
Chris Lawn (QMUL)	Thermal flow physics authority
Massimiliano Materazzi (UCL)	UCL team lead and plasma gasification authority
Andrea Paulillo (UCL)	Life Cycle Analysis authority
Vladimir Prodaevich	Triboelectric plasma technology authority, zero-cost project partner

Stuart Wagland (Cranfield)	Cranfield team lead and waste gasification and management authority

Three researchers will be employed at 100% time for the full duration of the project: Researcher 1 (Modelling, QM), Researcher 2 (Experimental plasma gasification, UCL), and Researcher 3 (Experimental gasification and waste management, Cranfield)

A commercialisation officer will be employed at 100% time for the last 6 months of the project. This appointment will be aligned with the spinout activities in the last phase of the project.

A professional project manager will be employed at 50% time for the full duration of the project, who will be responsible for organising the project meetings and also ensure compliance with the BEIS standards and practices. In addition, the project manager will coordinate the staff secondments such as from London to Cranfield, as well as the preparation of periodic reports for BEIS.

Details of the estimated costs for the Phase 2 project are provided as an annex to the report.

6.3 Risks and risk management

Severity, probability, and type	Risk	Mitigation plan
Major, medium, technical	The recirculation gas streams do not generate sufficient triboelectric power to form plasma	Increase the inlet flow speed. Introduce tribolectrically active particles in the syngas inlet.
Major, medium, technical	The triboelectric plasma forms but does not generate a sufficient temperature for tars reforming	Increase the inlet flow stream speed to enhance the triboelectric process. Include oxygen in the syngas inlet stream to ignite the process after which the oxygen supply is turned off.
Medium, high, schedule	The delivery of materials and parts for commissioning the reformer reactor, many of which will be coming from Europe, is delayed	Diversify the network of suppliers
Medium, medium, commercial/technical	The prototype reformer technology does not reach the required TRL 5-6 at the end of the Phase 2 project required for commercial applications	An advisory board will be formed consisting of the key industry players in the energy and gasification sector. The board will provide regular feedback to the project to ensure

		that the results are transferrable to industrial applications after the end of the Phase 2 project.
Medium, medium, commercial	The 2 companies - potential end-users of the triboplasma technology outlined in Section 7.4.2 may not be sufficiently interested to engage with us in Phase 3	In the last 6 months of the project, we will perform an extensive marketing research to identify and engage with a wide range of potential end-users from gasification sector, beyond the current list of the companies.

6.4 Quality assurance

The team of investigators includes experienced researchers with a proven track record of delivering rigorous research outputs for various funders including BEIS, UKRI, and European Commission. In addition, the team includes a professional project manager and a commercialisation officer who will support the compliance with BEIS practices and commercialisation aspects.

6.5 Project oversight and governance

The project team will meet bi-weekly online and in-person every three months.

An advisory board will be formed consisting of the key industry players in the energy and gasification sector approximately at month 12 of the project. The board will provide regular feedback to the project team.

6.6 Reporting plans

Reports will be prepared quarterly to detail the project progress and milestones achieved, describe the deliverables in-period and update the risk register.

6.7 Plans for disseminating the demonstration results and key learnings to relevant industry sectors

Preliminary results of the Phase 1 project were disseminated at research meetings with Aston and Cranfield Universities as shown in the table below:

Title of Activity	Category of Activity	Description of Activity	Stakeholders Engaged	Date
Joint workshop with the Aston University	Presentations at a research group	Presenting our research at a joint workshop with the Aston University	10	10/10/2022
Joint workshop with the Cranfield University	Research presentations and discussions	Presenting our project to the gasification expert at the Cranfield University	3	21/10/2022

Results of the Phase 2 project will be disseminated at major UK and European conferences in which the relevant industrial representatives from the energy and gasification sector are present.

Two industry workshops will be held at Cranfield University at month 14 and month 22 of the programme to introduce the technology to industry and disseminate the key results, respectively. Industry representatives and potential customers of the new triboplasma gasification technology will be invited free of charge. Preliminary contacts with the key players from industry, including BOC Linde, Equinor, BP, ABSL, Innovyn, Shell Hydrogen, Siemens, and SSE have already been made.

7 Commercialisation plan

7.1 Target Market Description

The addressable market for our triboelectric gasification technology is the developing market for low-carbon hydrogen in the UK. Low-carbon hydrogen is an essential component to achieving the UK net-zero targets and is forecast to have a significant role in the decarbonisation of the industry, transport, heat and power sectors. The Climate Change Committee, Aurora Energy Research and National Grid, forecast a rapid growth in demand for low-carbon hydrogen over the next two decades, reaching an estimated 375 TWh by 2050, with the UK Hydrogen Strategy predicting that hydrogen will represent 20% - 35% of UK energy consumption equating to 250 – 460 TWh of hydrogen. The early adopters of low-carbon hydrogen will be industrial users such as refineries, ammonia producers and glass manufacturers, together with specific difficult to electrify transport sectors such as taxis, buses, heavy goods vehicles and shipping. Long-term demand will be driven by the phasing out of gas for domestic heating and the adoption of a blended natural gas/hydrogen approach.

By comparison current UK hydrogen production is small (~10 - 27 TWh), based on fossil fuels (termed grey hydrogen) and is concentrated in the petrochemical industries. Given this relatively low base, the UK Government has committed to supporting low-carbon hydrogen production in the near term and to deliver 5GW of low-carbon capacity by 2030, followed by a rapid scale up by the mid-2030's in order to meet the 2050 target. This represents a significant near-term target market for our triboelectric gasification technology. An ancillary near-term target market is the production of sustainable fuels for sectors difficult to decarbonise (e.g. aviation) that can act to provide revenues as the low-carbon hydrogen market develops and becomes established.

This demand for hydrogen will be met by the following technologies:

- Grey Hydrogen – (high-carbon) hydrogen production from the reformation of natural gas or methane
- Blue Hydrogen – (low-carbon) hydrogen production from natural gas reformation combined with Carbon Capture and Sequestration (CCS)
- Green Hydrogen – (low-carbon) hydrogen production through the electrolysis of water powered by renewable energy
- BECCS – (low-carbon) hydrogen produced from the gasification of biomass and waste streams combined with CCS

The forecast cost breakdown is given in the table below.

Hydrogen Production	Cost: 2020 – 2030 (£/MWh)	Cost: 2050 (£/MWh)
Grey	64	130
Blue	59 - 62	65 - 67
Green	112	71
BECCS	95 (excl carbon) 41 (incl carbon)	89 (excl carbon) -28 (incl carbon)

Source: UK Hydrogen Strategy, August 2021

The main driving factors are:

- Green Hydrogen
  - Operating Cost: price of renewable electricity and electrolyser load factor and efficiency
  - Reliability: intermittent due to reliance on renewable energy sources
  - Capital Cost: Significant
- Blue Hydrogen
  - Operating Cost: price of natural gas and cost of CCS
  - Reliability: stable
  - Capital Cost: Significant
- BECCS (triboelectric)
  - Operating Cost: dependent on waste gate fees, scale of the production plant and cost of CCS
  - Reliability: stable but reliant on availability of suitable feedstock ie biomass and/or Municipal Solid Waste (MSW)
  - Capital Cost: Medium - triboelectric plants are economically viable at a smaller production volume compared to Blue Hydrogen ie a triboelectric plasma reforming plant would be profitable at a capacity of 30 MW hydrogen HHV.

The mix of technologies used in the future hydrogen economy will depend on a range of factors, but it is clear from the cost breakdown and the existence of the current installed base of Grey Hydrogen plants, that the focus will be on Blue Hydrogen in the near term. However, the similarity of the 2050 cost forecast indicates that that the demand for low-carbon hydrogen will be met ultimately by a mix of the technologies. This is recognised by UK Government who are committed to pump-priming the sector to deliver a world-leading mixed hydrogen economy.

However, hydrogen BECCS is differentiated from the competitor technologies through two additional key advantages:

7.2 Offsetting Negative Emissions

The BECCS process provides negative emissions as the carbon dioxide captured from the atmosphere by the biomass feedstock is then sequestered during the hydrogen production process. The negative emissions can be used to offset emissions from industrial processes that are difficult to decarbonise. Deploying BECCS hydrogen production at scale will therefore make a significant contribution to the UK Governments Greenhouse Gas Removal (GGR) of 5 Mt CO2/year by 2030, a key element of the net-zero strategy. Hydrogen BECCS could therefore form part of an industrial cluster strategy providing low-carbon fuel and offsetting carbon emissions from carbon-emitting processes. The lower production capacity required for economic viability for hydrogen BECCS (30 MW hydrogen HHV) enables such a distributed model.

7.3 Improved Financial Model

The BECCS technology has the potential to extend beyond the low-carbon hydrogen target market and disrupt the current waste-to-energy (WTE) market and industry. WTE is therefore a secondary target market for hydrogen BECCS once the technology has been established at scale in the hydrogen economy.

The current WTE business model is based on local contracts to manage waste collection, treatment and disposal. Although there is a continuing focus on reducing and recycling waste, approximately 26 Mt (2018 figures) of residual MSW is generated in the UK with approximately 7 Mt still being sent to landfill and the same mass treated and sent to WTE incinerators. The latter accept either MSW directly or MSW that has been dried and shredded to form Refuse Defined Fuel (RDF). At a net 7 GJ/tonne, the energy content of the incinerated waste is approximately 2% of the annual UK gas consumption. However, the incinerator technology operates at efficiencies of only 11% - 16% when CCS is installed, or 25-35% when they do not deliver process steam or district heating. In addition, removing CO2 from an incinerator flue gas is significantly more difficult than removal from syngas (as it would be in H2BECCS), due to the high dilution in nitrogen in the former case, and the lower (CO2) partial pressure. Finally, the ash waste from incineration is regulated and needs to undergo an expensive process of extraction and treatment before being partially recycled as construction aggregates.

BECCS gasification has the potential to transform the existing WTE business model and industry through an improved financial operating model focused on waste-to-fuel (WTF). A thermochemical plant based on gasification operates at significantly higher conversion efficiencies (defined as energy output in fuel divided by energy input in feedstock) of 60% minimum, and produces high value low-carbon hydrogen and chemical products (CCS can be used to remove the CO2 generated). However, the elimination of the need manage incineration waste is a key financial benefit as the existing process is expensive and likely to be constrained in the future through increasingly restrictive environmental legislation/regulation, which is a key risk to the existing WTE business model.

7.4 Commercial Deployment Plan

7.4.1 Phase 2: Dirty Syngas Reformer (2023 – 2025)

Phase 1 of this project has established the proposed design and operational envelope for a pilot-scale triboelectric plasma-based dirty syngas reformer. Phase 2 will construct and install the reformer which will be attached to a dirty syngas supply at Cranfield University. The design from Phase 1 divides the reformer flows into two streams: input syngas feedstock (~15kg/hr) and ash-laden recirculating gas (~1000 kg/hr). With the latter being at the appropriate scale for a full reformer plant.

The objective of this phase of the project is to demonstrate that the triboelectric plasma reformer:

- Design is viable and that the triboelectric plasma operates effectively initially with artificial dirty syngas
- Can remove the tars and heavy hydrocarbons in the dirty syngas
- Operates continuously with at-scale flow recirculation (1000 kg/hr) and meaningful syngas throughput (15kg/hr)
- Demonstrates the significant order of magnitude improvement in the triboelectric energy balance

The key performance parameters for this Phase will be:

- tar conversion efficiency
- H2:CO ratio at the inlet and outlet of the reformer
- fly ash removal efficiency (compared to conventional plasma reformers)
- triboelectric plasma energy balance
- Wear and longevity of critical components within the design

The proposed scale is sufficient to prove the generation of triboelectric plasma and its effect on syngas composition that will move the reformer technology cost-effectively from the current TRL4 to TRL 6. Phase 2 of this project will therefore successfully de-risk the triboelectric plasma technology and derive key performance parameters for the reformer that will enable engagement with industry partners, funders and investors to scale the technology to the next level.

The latter stages of the project will focus on engagement with companies operating within the sector to organise a consortium to develop the next stages of the commercialisation of the technology through:

- Two industry workshops to be held at Cranfield University at month 14 and month 22 of the programme to introduce the technology and disseminate the key results respectively
- The formation of a spin-out company at month 22 that will have the requisite rights to the technology and underlying IP. The company will act to manage the IP rights of the university partners and also as a vehicle for the ongoing Ip management ie providing a simple contractual interface for external partners.
    - The spin-out company will be supported by Queen Mary Innovation Ltd which is the technology transfer office of Queen Mary, University of London

Engagement with industry will be a focus of the Phase 2 programme and the following potential partners have already been contacted:

- BOC Linde
- Equinor
- BP
- ABSL
- Innovyn

- Shell Hydrogen
- Siemens
- SSE

The sector is currently seeing significant investment, BP has recently purchased biogas company Archaea Energy for $3.3 billion demonstrating the significant value in the sector. Archaea is a US renewable natural gas produced with 50 landfill gas-to-energy facilities across the US. The purchase aims to strengthen BP's biogas division which is one of the 5 strategic growth areas identified by BP.

7.4.2 Phase 3: Scaled Reformer Pilot-Plant (2025 – 2028)

The results from the Phase 2 programme will be used to develop the design of a full-scale stand-alone reformer that will be constructed, installed and tested in an existing steam-oxygen gasification plant during Phase 3. The objective for pilot-plant is to demonstrate that triboelectric plasma technology can:

- Remove the tars and heavy hydrocarbons in the syngas generated from an existing gasification plant operating at all points within the operating envelope
- Operate at an industrially meaningful contaminated syngas throughput of ~100kg/hr
- Demonstrate of the economic viability of the proposed fully integrated gasification system

The key performance parameters for the demonstration will be:

- tar conversion efficiency
- H2:CO ratio at the inlet and outlet of the reformer
- fly ash removal efficiency (compared to conventional plasma reformers)
- overall efficiency of the reformer over key operating points within the operation envelope

The size of the pilot is dictated by the maximum amount of syngas slipstream that can be extracted from the hosting gasification plant without impacting on the plant financial contracts in place. Phase 3 of this project will therefore successfully de-risk the triboelectric plasma reformer technology and derive key performance parameters that will enable the release of investment for a full scale triboelectric based gasification plant.

Two existing gasification plants that operate a suitable 2-stage model have been identified:

- Advanced Biofuel Solutions Ltd (ABSL) – Swindon plant
- Kew Technology Ltd – Wednesbury plant

Discussions have been started with ABSL and will be initiated with Kew Technologies.

7.4.3 Phase 4: Triboelectric Gasification Plant (2028 – 2031)

Given that all other processes used in biohydrogen are well established, we believe that the first scale triboelectric gasification plant with throughputs of ~1000 kg/hr can start operation during Phase 4 by end of 2031. Although the plant will not be fully economically viable at this scale, by removing the biggest technical challenge in biomass gasification for BECCS, i.e. tar, triboelectric plasma based gasification will integrate with and benefit the entire Hydrogen BECCS process chain.

On run-up, the plant would use 10% biogenic biomass such as waste wood pellets as the input feedstock in order to deliver the required outputs without CCS early in this phase of the programme. The plant would be modified over the last 12 months of the project to operate with the more complex RDF feedstock ie by 2031.

7.4.4 Phase 5: FOAK Gasification Plant (2031 – 2036)

The final phase will be the construction of a full scale economically viable hydrogen BECCS plant based on triboelectric plasma gasification operating at a throughput of 100,000 kg/hr. The plant would require CCS infrastructure to deliver very high GHG savings and therefore is suited to installation in industrial clusters where such technologies exist, such as Teesside and Humberside. The use of biohydrogen without CCS can still provide GHG emission savings relative to incumbent fuels and converts waste streams into a valuable product, with hydrogen a higher value output than electricity from energy from waste plants.

There could therefore be a degree of flexibility with regard to siting some of the plants at locations without CCS infrastructure across the UK, although the full benefits of the technology would require siting around the industrial clusters, or locations with carbon dioxide demand. As noted previously, biohydrogen technology can also be deployed at far smaller scales than blue hydrogen, allowing it to offer a more distributed approach to hydrogen production.