RISING PRESSURE REFORMER (RIPR) FOR HYDROGEN PRODUCTION

BEIS Hydrogen BECCS Innovation Competition:
Phase 1 Report

HELICAL ENERGY

Cranfield University

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2 Executive summary

This report describes and illustrates the feasibility of a radical disrupter in the hydrogen market known as Rising Pressure Reformer (RiPR). This innovative technology aims to decarbonise hard-to-abate sectors to pave the way for carbon negative hydrogen production. Directly tackling climate change, RiPR removes carbon dioxide with hydrogen production therefore increased hydrogen production will result in increased carbon dioxide removal from the atmosphere.

Whilst hydrogen doesn't produce carbon dioxide at end use, the vast majority of hydrogen produced today is from fossil fuels, releasing 830 million tonnes of carbon dioxide (CO_2) into the atmosphere every year – equivalent to the entire CO_2 production of the UK and Indonesia combined[1]. This project has demonstrated the feasibility of RiPR technology as a means to produce carbon negative, low-cost hydrogen.

This report summarises the work of Helical Energy and Cranfield University in establishing the feasibility of our proprietary technology, a suitable feedstock, and the role of Clear Hydrogen* within the commercial market. The outcomes of the project are:

- The technology has a very low levelized cost of hydrogen (LCOH) as concluded through a technology costs report (CAPEX and OPEX) for a full scale plant.
- There is a growing, strong market for low-cost carbon negative hydrogen, across a number of industrial sectors
- The RiPR technology is able to utilise low-cost and readily available sources of biomass feedstock (green waste, industrial waste, and arable)

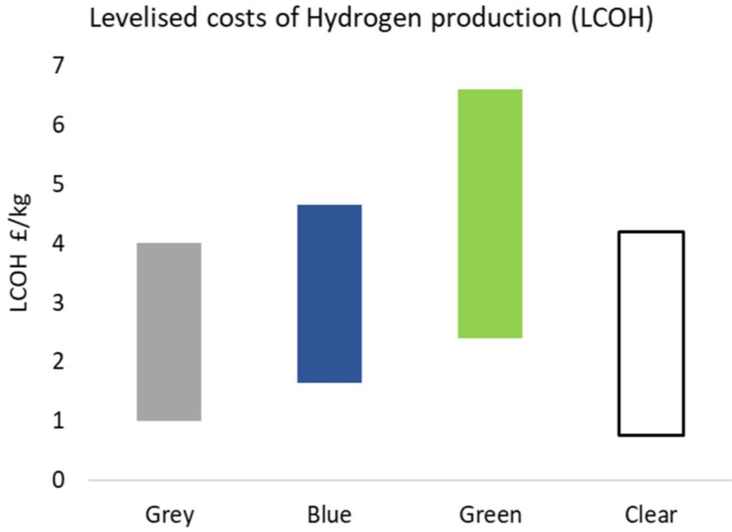
As a result of this project, we have found that producing carbon negative and cost competitive hydrogen is technically feasible and scalable. The team are looking forward to the next phase of the project to build a fully scaled demonstration plant.

*Clear Hydrogen is the given name of hydrogen produced using RiPR technology.

3 Introduction & Project Overview

The primary challenges for hydrogen production are cost reduction and carbon emissions. Whilst hydrogen use often doesn't emit any carbon dioxide, current blue and grey hydrogen production methods do. Green hydrogen production methods, though carbon neutral, cannot compete on a cost basis.

The aim of this project was to prove the feasibility of the RiPR technology to produce carbon negative and cost competitive Clear Hydrogen on a commercial scale.



RiPR technology and key benefits

The Rising pressure Reformer (RiPR) is a technology that utilises biomass to produce a hydrogen rich syngas. The technology is compatible with a wide variety of innovative biomass feedstocks due to the versatility of our proprietary gasification process. The RiPR can utilise feedstocks with a high moisture content, handle a highly variable feedstock particle size, doesn't need a consistent feedstock composition, and is less sensitive to carbohydrate substrates within the feedstock. This makes the RiPR exceptionally more flexible, cheap, and efficient compared with other gasification technologies (e.g., AGTs). For these reasons, the RiPR is a radical disruptor in the UK clean energy market.

Feedstock survey

A feedstock survey was undertaken, assessing the attractiveness of biomass as a potential feedstock. These were divided into: biogenic wastes and residues; domestic and arable crops; perennial energy crops and short rotation forestry; UK derived forest products; and marine-based and other novel feedstocks. The ability of each feedstock to meet government policy aims, feedstock availability requirements, and impacts on the LCOH were assessed. The assessment concluded that the demonstration unit is necessary to validate the use of these various feedstocks and measure the composition of the generated syngas

4 Experimental results

A test program (called Nano-RiPR) was developed to close the gap arising from the limitations of the ANSYS simulation software in modelling supercritical performance and to further validate these simulation results. Experimental results using the ‘Nano’ prototype have been obtained which can be cross referenced with tests simulated by ASPEN. The results of the trials are an improvement in hydrogen yield vs the ASPEN simulations improving the confidence levels of the technology.

5 Commercial demonstrator

The size of the commercial demonstrator has been selected to closely align with the scale of a commercial sized RiPR whilst remaining within the phase 2 budget. The plant will be fully instrumented, piped and valved to allow the full series of tests to be carried out to demonstrate the operational feasibility of the technology. A centralised plant control system will manage plant control and monitoring with a separate and dedicated hardwired shutdown system.

6 Environmental considerations: a Carbon Life Cycle assessment

This carbon life cycle has been conducted with the assumption *Miscanthus sp.* will be used as feedstock.

6.1.1 Full of CO_2e for a RiPR plant build and operate over 30 years

Table 1. Considerations made in order to assess the carbon life cycle of the RiPR plant build, operation over 30 years and decommission, including assumptions made to reach figures.

Category	Type	Units	Amount	Tonnes CO_2e per unit	Total CO_2e Tonnes	Data Source	Assumption
Build	Steel	Tonnes	3000	1.85	5,550	*2*	Steel required for all vessels and superstructures
	Cabling	km	10	15.75	158	*3*	Cabling for all electrical connections
	Pipework	Tonnes	5	1.85	9	*2*	Pipework for the plant
	Concrete	Cubic Metres	1000	0.653	653	*4*	Concrete required for all civils - greenfield site
	Buildings	Cubic Metres	600	0.653	392	*4*	Control and feedstock buildings
	Other Components	Tonnes	1000	1.85	1,850	*2*	All other components - based on steel
	Consumables	Tonnes	3000	2.68	8,040	*8*	Assume worse case based on diesel fuel CO_2e
	Personnel	Person years	300	3	900	*5*	Team of 100 FTEs for 3 yrs
Total					**17,552**		
Operate (30 years)	Personnel	Person years	1500	3	4,500	*5*	Team of 50 FTE operatives for 30 years
	Consumables	Tonnes	18000	2.68	48,240	*8*	Assume worse case based on diesel fuel CO_2e
Total					**52,740**		
Decommission	Steel	Tonnes	3000	0.37	1,110	*6*	Assume Steel is recycled
	Buildings & Concrete	Tonnes	1600	0.0077	12	*7*	Assume all concrete is recycled
	Personnel	Person years	50	3	150	*5*	Assume 50 FTE for one year
	Consumables	Tonnes	1500	2.68	4,020	*8*	Assume worse case based on diesel fuel CO_2e
	Other Components	Tonnes	1000	0.37	370	*2*	Assume worse case based on Steel
Total					**5,662**		
Grand Total					**75,954**		

Our data sources indicate the total CO_2e emissions released as a result of building, operating and decommissioning our technology is 75,954 t.

6.1.2 Carbon assessment of biomass feedstock (*Miscanthus sp.*) and emissions associated with land use change

According to the 2012 UK Bioenergy Strategy, the potential land available for Miscanthus that would not interrupt food production is 0.72-2.8 Mha which far exceeds the target of using 0.35 Mha for perennial energy crop growth set by the 2007 UK biomass strategy. Miscanthus being a crop that uses resources, water and nutrients extremely efficiently allows it to grow in a wide range of environmental conditions including marginal land as well as land contaminated with heavy metals[9,10].

Giant Miscanthus, a C4 plant absorbs and fixes more CO_2 through photosynthesis than C3 plants, such as those found in marginal grasslands. The carbon sequestration effects of Miscanthus, especially within its underground tissues which are not harvested are advantageous compared to other bioenergy crops. This perennial crop can be harvested for 25 years once planted meaning it does not need regular ploughing each year reducing its emissions.

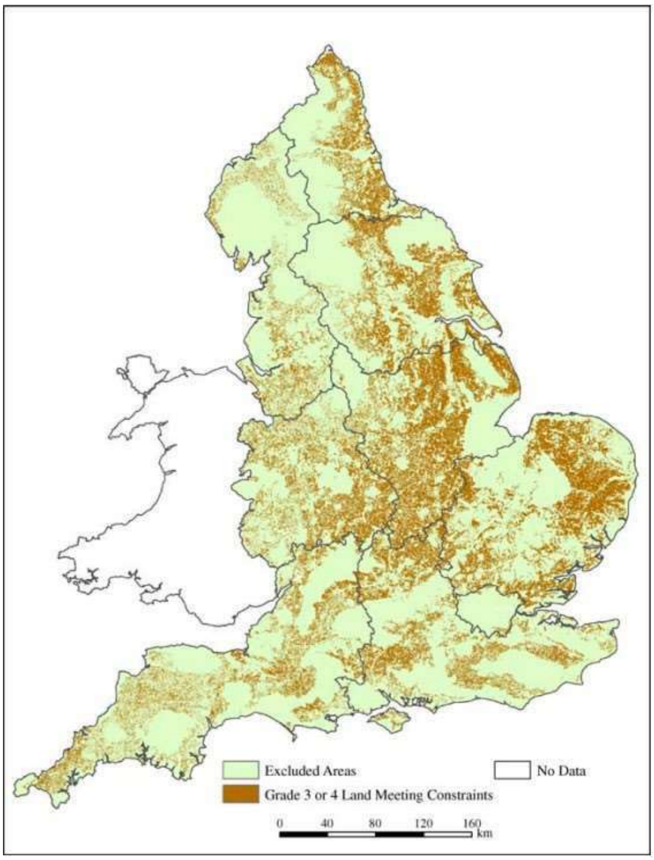


Figure 3. Constraint map taken from Lovett and others indicating 3.12 Mha is available in England alone for growth of Miscanthus. Areas excluded cover biophysical, social and environmental considerations as well as only including poorer quality land in agricultural land class (ALC) grades 3 and 4 but excluding the worst grade 5[11].

To assess the net carbon impact of this feedstock, the following considerations were made[12]:

- Soil preparation: spraying, ploughing, harrowing and tilling
- Planting: planting material cultivation, planting material logistic and machineries involved.
- Harvest operation: cutting/swathing, baling, bale movement and loading and bale transport.
- Field emissions: biomass litter (leaves, stubbles), and GHG escape (NOx, NHx, etc.) from fertilization.
- Soil organic carbon (SOC) change: soil carbon sequestration, cultivation period, biomass C content, and biomass litter (leaves, stubbles).

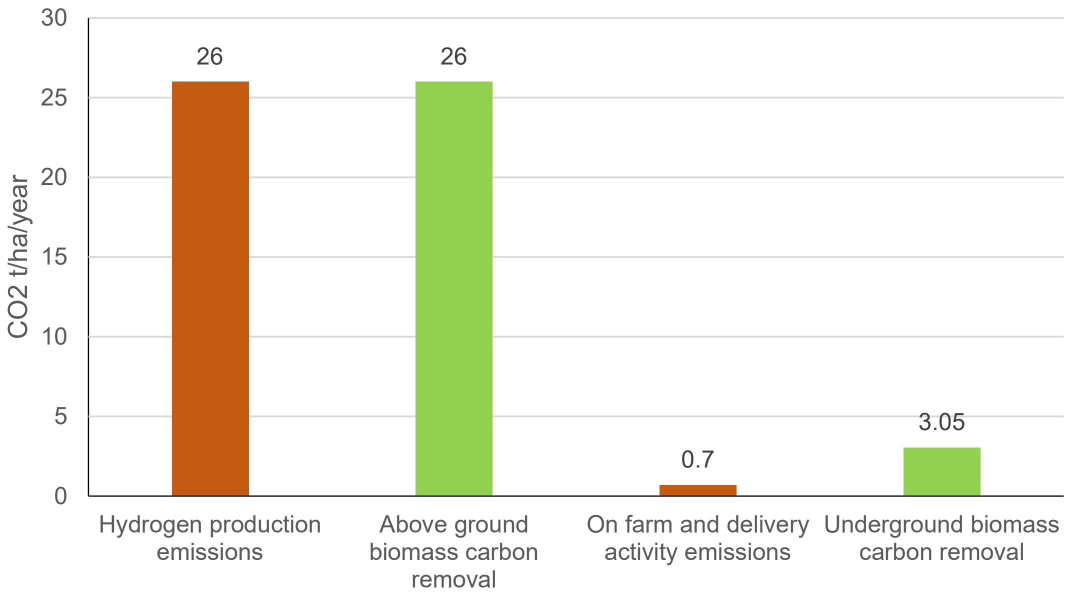


Figure 4. Considerations for carbon emissions and carbon removal, indicating that a net carbon capture of 2.35 t/ha/year of CO_2 would result during the process of producing hydrogen from Miscanthus, excluding our carbon capture technology. [Data obtained from ref. 12].

To further corroborate these data, Robertson *et al.* found that Miscanthus removes 24.5 t/ CO_2-eq/ha/year from the atmosphere[13]. The farm and transport activity emissions are low compared to the carbon uptake of Miscanthus, whereby even when food production is displaced by bioenergy feedstock production Miscanthus offers GHG savings when considering indirect land use[18].

Soil organic carbon

There have been concerns that the carbon mitigation benefits of Miscanthus could be outweighed by losses in soil organic carbon (SOC) levels associated with land use change of grasslands. However, the evidence indicates that there are no significant SOC changes, as the C4 Miscanthus carbon replaces the initial C3 grassland carbon[14]. There is an initial short-term loss of carbon in the soil during traditional establishment (spraying, ploughing, tilling, and planting), though it quickly recovers as the crop matures and can in fact lead to an increased accumulation of SOC comparable to agricultural grassland within the lifetime of the crop[15].

Fertiliser (Nitrogen)

Miscanthus is generally unfertilised in commercial production except during establishment in soil with a very poor nutrient status[15]. Nitrous oxide (N_2O) production, with its extremely powerful global warming potential is particularly a concern when growing bioenergy crops, as it can easily offset the carbon mitigation effects of Miscanthus. The crop may benefit from low levels of nitrogen fertiliser application in early rhizome development where soils have particularly low nitrogen levels, however generally due to its high nitrogen use efficiency, Miscanthus does not need nor respond well to nitrogen fertiliser[16].

Roth *et al.* found converting a grassland to Miscanthus field which has not been fertilised with nitrogen has a neutral impact on N_2O emissions in the medium- to long-term[17]. There is some evidence concerning soil N_2O emissions that suggests unfertilised Miscanthus has a mean N_2O flux rate that is approximately 5x less than that of annual crops[15].

Though this is a beneficial quality of the crop, one trade-off of this low nitrogen requirement is that emissions and leaching may initially rise if planted in highly fertilised land as Miscanthus is unlikely to use the all the available nutrients during establishment. Miscanthus may therefore be better placed in low nutrient soils in marginal land as we intend. However, in the case it is grown in highly fertile land, a suitable cover crop could be planted during the transition that would take advantage of these nutrients[15].

Overall, the total CO_2e footprint for the RiPR plant build, run and decommission is 75,954 t compared with the total lifetime CO_2e absorption from the feedstock which is 9,328,846 t as seen in figure 1. Therefore, the use of RiPR technology in combination with the carbon capture and sequestration properties of Miscanthus uniquely enables an exceptionally carbon negative footprint.

7 Project Plan

7.1 Phase 2 RiPR demonstration location

The phase 2 demonstration plant will be located on a green fields site at Cranfield University

Approx. Plant co-ordinates: 52°04'07.0" North

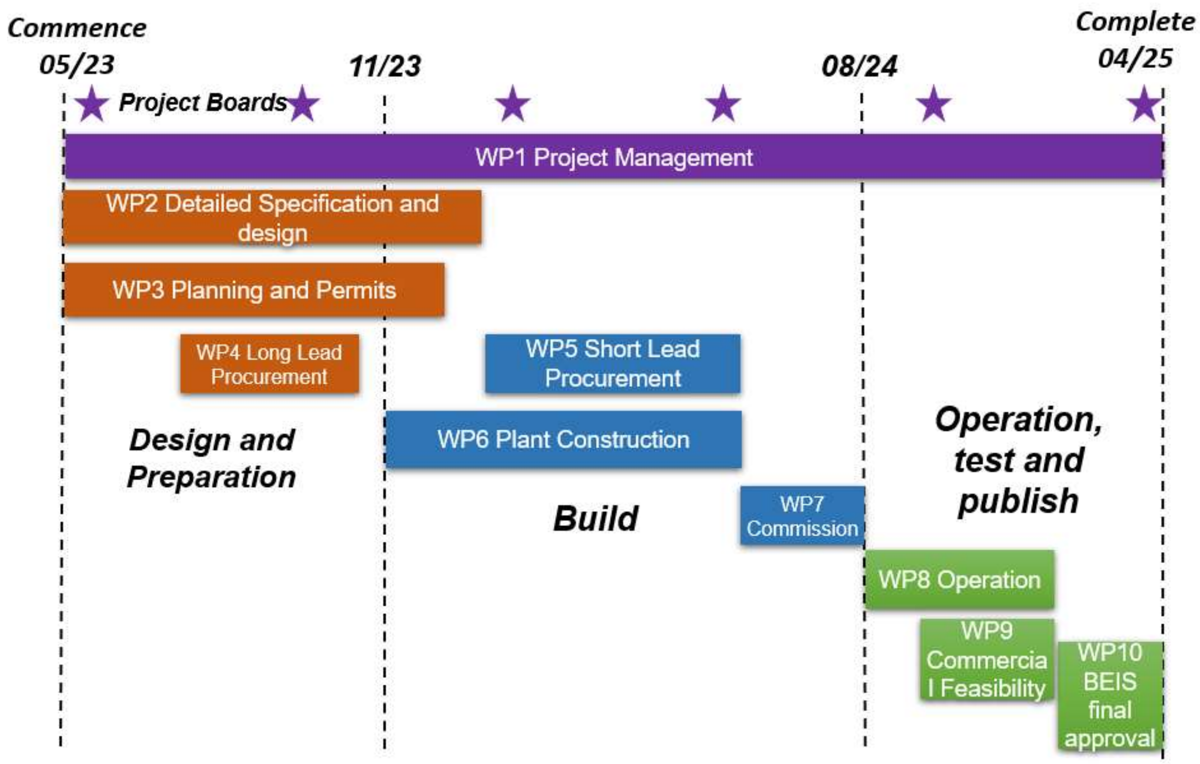
0°37'37.8" West

Reasons for location choice:

a) Central to the UK, with good transport links making it easy for key stakeholders to attend site visits
b) Infrastructure can support a high volume of site visits – car parks, visitor facilities etc.
c) Existing utilities (electricity, water, gas) that can be used
d) Physical access and facilities are in place for staff
e) The permits and permissions will be less onerous with shorter approval times and a higher likelihood of being granted at an existing research site
f) Within a good catchment area for operative labour
g) Cranfield technical consultancy team are on site and able to assist on short notice, reducing travel time
h) Easy access to several industry partners currently undertaking research at Cranfield could prove to be beneficial
i) Cranfield university is a world leader in the field of alternative energy and the association will add additional credibility to RiPR technology
j) Gas and feedstock analysis and equipment are on site

7.2 Project deliverable timeline

The high-level project deliverable timeline is shown below and is divided into several discrete and independent work packages



7.3 Project Management

The project will be managed based upon PRINCE2 and MSP (Managing Successful Programmes) methodology. The programme scope includes:

- Permits and permissions for the chosen location at Cranfield University
- Physical build to the engineering design specification
- Functional and performance testing
- The final deliverable will be a full report sharing the results, including an updated commercialisation plan to take the technology to the next step and ultimately to the market.

7.3.1 Phase 2 Partner Responsibilities

Helical energy will continue to be the lead organisation and manage the relationship with BEIS. Helical's primary responsibility will be Project Management, the Principal Designer and Principal Contractor (inc. detailed design, procurement, construction, installation and commissioning) for the project. Helical energy will also be responsible for providing engineering support during the operation of the plant. Helical energy are also responsible for the safety risk assessments (DSEAR, HAZID, HAZOP and LOPA).

Wild Hydrogen is responsible for report preparation, outlining governance responsibilities and shares project management responsibility. They will advise on the scalability of the demonstration plant design and review output data once in operation to enable a feasibility study for a commercial scale plant.

Cranfield University are responsible for providing the site, site utilities and overseeing the testing program and analysis of any samples. Once the demonstration plant is in operation, they will be responsible for collecting and analysing the process data. The university will also be performing system engineering modelling, which will be validated using the demonstration plant data. In addition Cranfield will also provide support for the planning and other consents required in respect of the demonstration plant. Cranfield and Helical will have shared responsibly in respect to the plant operation.

7.3.2 Work Packages

WORK PACKAGE	DESCRIPTION
1	Project management/other. All activities associated with BEIS required project management milestones
2	Plant detailed specification and design: Delivery of final process/mechanical/electrical design for demonstration plant. Design and safety reviews.
3	Planning and permitting: Activities related to gaining appropriate consent and planning for the installation of the demonstration plant.
4	Long lead procurement: Purchase of long lead equipment for the demonstration plant, in particular the RiPR assembly, long lead valves, ballast heater, control room, control system, gas analyser, stack and civil works.
5	Short lead procurement: Purchase of off-the-shelf and short lead equipment for the demonstration plant.
6	Plant Construction: Completion of ground works and plant installation
7	Plant commissioning and training: Completion of process commissioning for the assembled plant
8	Plant operation, data collection and process modelling: Operation and completion of key process research activities using the demonstration plant
9	Commercial scale feasibility: Review of commercial scale concept and feasibility based on available process data from operation of the demonstration plant. Preparation of commercial scale feasibility study.
10	BEIS final approval

7.3.3 Quality assurance

The project will be managed in accordance with Helical Energy's work procedures and quality management system certified to ISO 9001 : 2015 developed over years of successful project management and project execution experience. A Quality Management Plan will be developed that defines the quality control and assurance responsibilities. To achieve high quality deliverables, adequate time has been allocated to achieve thorough, accurate and reviewed work products with a 5-day period for board approval. Consequently, every team member and manager is responsible for quality. Quality delivery is a fundamental expectation of the team.

The project will generally adopt the following criteria to maintain data quality as follows:

1. Completeness – the data value reflects all the information it was designed to capture or convey, validity
2. Reliable – the data comes from a reliable source or process, is referenced appropriately and is double checked by another member of the team
3. Consistency – the same source or process produces the same data and the same data values for a given event or object should be reflected across the project
4. Timeliness – data should be sufficiently current for use, and;
5. Accuracy – the correct value should be recorded at the point of inception and this value is retained across the project

7.3.4 Governance of the project

Each partner has been assigned their own set of work packages to develop and will formally meet every fortnight to report progress against plan, raise and resolve issues and review risks. Project boards comprising representatives from the partners will meet monthly to report progress against plan, review products, risks and resolve any escalated issues. If necessary extraordinary boards will be convened to ensure unresolved escalated issues do not delay the project. A dedicated project manager will be assigned as the single point of contact with the BEIS monitoring officer to communicate progress, costs and risks.

7.3.5 Reporting plans

Reporting plans will be developed together with BEIS but will include progress against plan (time and budget), escalated risks, issues and preliminary results when available.

7.4 Dissemination

A PR video and a technical report will be sent detailing the results and key learnings to the relevant industry sector contacts many of whom were obtained during this Phase 1 feasibility study. An updated commercialisation plan will be completed in Phase 2 to outline exactly how this will be carried out.

8 Commercialisation

The Rising Pressure Reformer (RiPR) is a technology that produces a hydrogen-rich syngas compatible with a wide range of biomass feedstocks due to its flexible nature. RiPR utilises feedstock with a high moisture content, can handle highly variable feedstock particle size, does not need a consistent feedstock composition and is less sensitive to the carbohydrate substrate of the feedstock making it exceptionally more flexible, cheap and efficient compared with other advanced gasification technology (AGT).

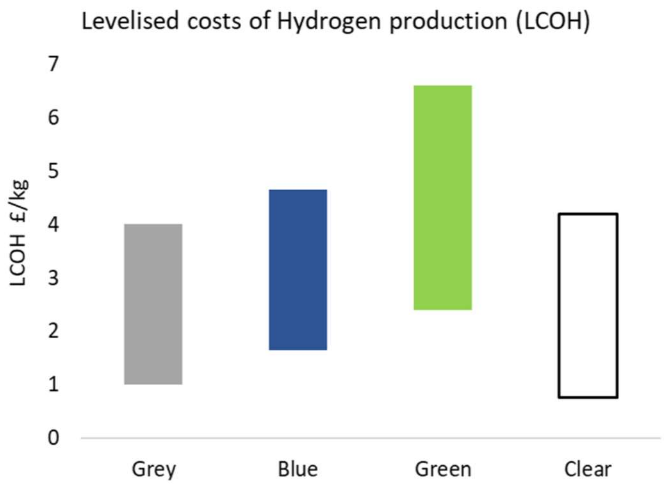
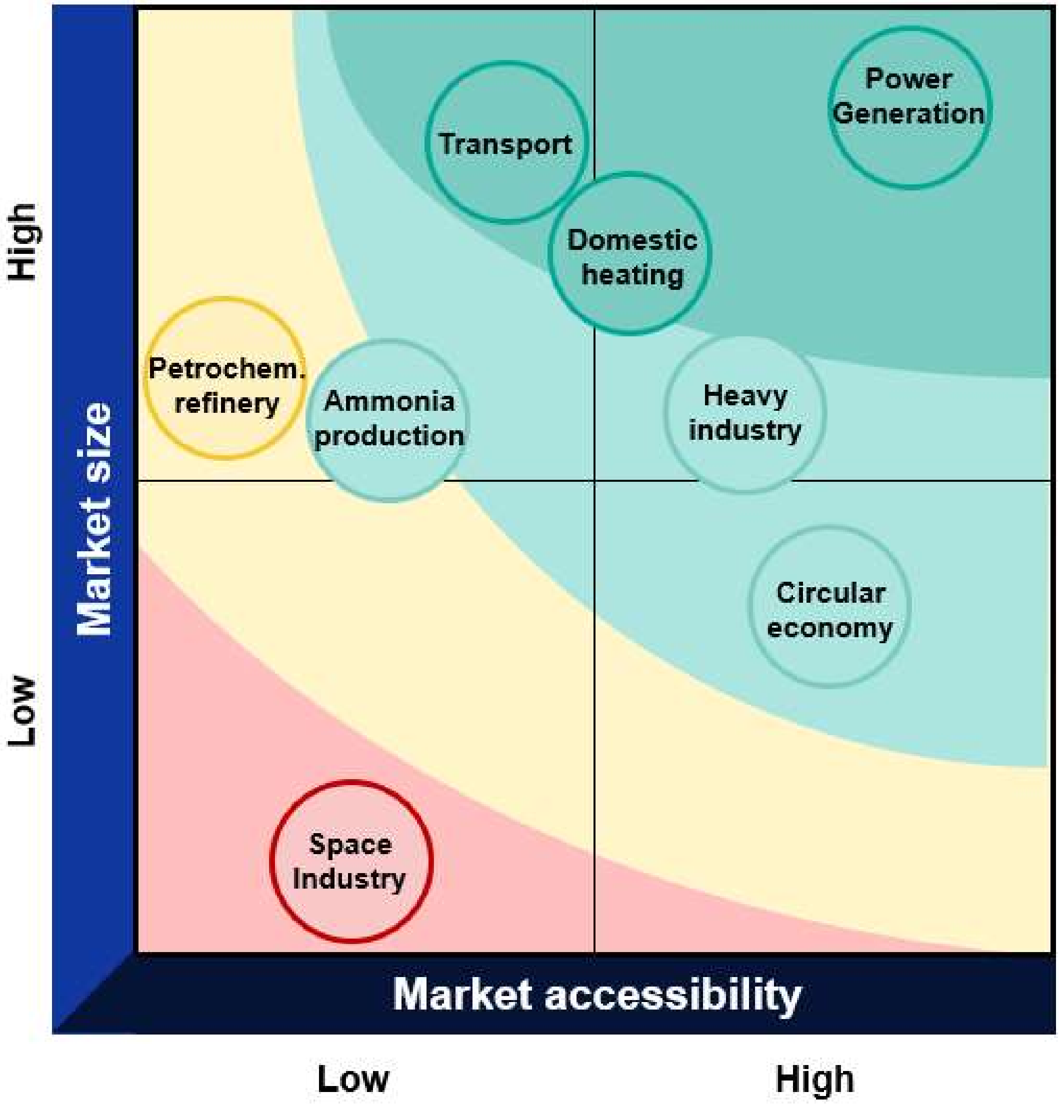


Figure 5. illustration of Clear Hydrogen vs competitors in regard to the LCOH

There are two key elements of RiPR technology that result in its lower levelized cost of hydrogen (LCOH) in contrast to comparable technologies. Firstly, the lack of requirement for pre-processing of feedstock enables RiPR to use biomass AGT processes cannot. Secondly, hydrogen is produced at pressure resulting in a less severe energy penalty if high-pressure hydrogen is required post-production

8.1 Market overview

The market was assessed based upon two metrics, size and accessibility. Location of hydrogen production was also considered. The following markets were identified:



Power generation

This appears to be the most attractive market, being both large in size and highly accessible due to the simplicity of driving a gas turbine using hydrogen. The location of hydrogen production within this market would be near feedstock cultivation, as the national grid is easily accessible.

Transport

Though of significant size, this market is less accessible due to its reliance on current development of innovative technology such as hydrogen internal combustion engines which are better suited for heavy transport vehicles with high power demands, e.g., construction vehicles and aircraft[19]. We are closely following these developments currently being carried out by the likes of JCB, Rolls Royce, EasyJet and ZeroAvia. There is, however, a current market for fuel cells which require a higher purity of hydrogen, and potential to convert diesel-electric hybrid trains to hydrogen-electric hybrids. The location of hydrogen production within this market would be near the end user, to minimize the cost of hydrogen transport.

Domestic heating
Our technology can support creating a blend of up to 20% hydrogen in the natural gas grid, as outlined by the UK Government Hydrogen Strategy. Moreover, 15% of UK homes rely on LPG and other fuels, which can be replaced with hydrogen[20]. Location of hydrogen production will be dictated by areas of the gas grid with high pressure connection.

Heavy industry
Involves energy intensive processes making it a promising market due to our competitive LCOH. Hydrogen production will be located closer to the end user within this market.

Circular economy
Paper production and wastewater treatment are energy intensive, with wastewater treatment consuming 1-3% of the global energy output. Using waste to produce energy would result in circular economy benefits. This can be supplemented by for example, purifying CO2 produced by RiPR technology for its cryogenic purposes as well as for fizzy drinks in the beverage industry. To maximise circular economy benefits, hydrogen production will be near or adjacent to the end user to easily process waste as feedstock.

Petrochemical refinery
Though petrochemical refinery is a substantial market, it is less accessible due to the pre-existing grey hydrogen market being well established within the larger fossil fuel industry with the few, but large customers such as BP already having capital investments in grey hydrogen. Hydrogen production would be located near its end use, i.e., a petrochemical refinery plant.

Ammonia Production
Ammonia production is more accessible with opportunity for new entry, e.g., the largest manufacturer of ammonia in the world, CF industries have announced their plans to use green hydrogen. With our competitive LCOH, our technology is well placed to succeed in this market. Hydrogen production would be near the site of feedstock cultivation, due to ammonia being cheaper to transport compared with hydrogen.

Space Industry
There is a small, niche liquid hydrogen market within the space industry though this remains decades away from significant development resulting in it being less accessible. Due to the very high hydrogen demands, production would be near its end use within this market

8.2 Commercialisation plan

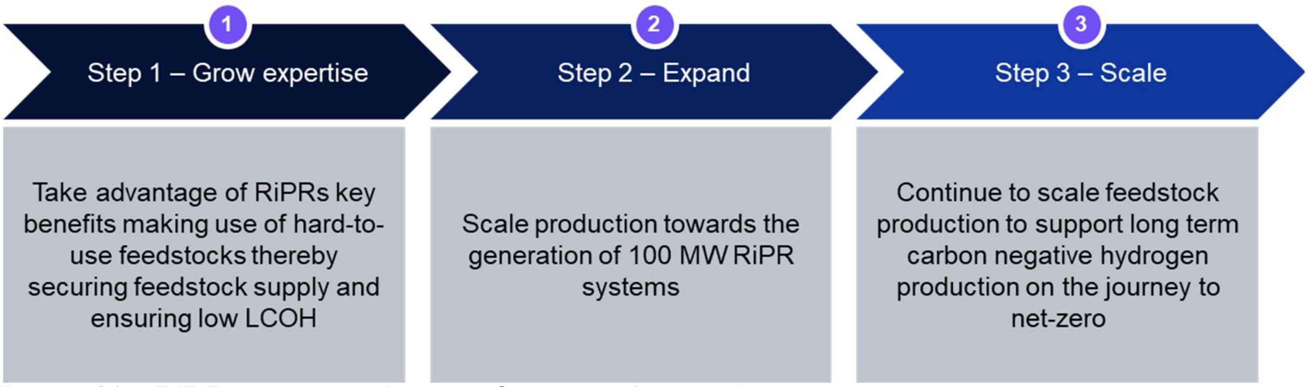


Figure 10. RiPRs commercial plan follows a 3-step development plan

The current commercialisation plan aims to take advantage of RiPRs benefits over other AGT processes. Since RiPR can accept a wide range of feedstocks, initially we plan to use feedstocks that are less desirable to other biomass users, e.g., the biogenic fraction of municipal waste such as oversize compost. It may be possible to receive some, if not all of this feedstock at a low, or even negative cost since waste producers often pay a fee for disposal services. This low-cost feedstock will be used to solidify our expertise, build scale and streamline operational efficiencies.

Once we have demonstrated the commercial viability of RiPR, we will begin to scale production towards the generation of a combined 100 MW RiPR system. Feedstock will shift to categories with higher available volumes such as forestry wastes and residues (currently used in UK biomass power stations) to support this scaling effort. During this shift, feedstock composition may be highly variable which RiPR is well positioned to process, giving it a major advantage over other AGT processes. In line with government policy, the focus is likely to be placed on using biomass to serve end users in hard-to-abate sectors on the journey to net zero. This is likely to include industries that produce feedstock as a waste by-product (e.g., the paper production industry) enabling potential circular economy dynamics.

In the long term, so long as feedstocks are scaled to support the expansion of RiPR technology, by virtue of our low LCOH, the grey hydrogen market could be partially substituted supporting the industrial sector’s journey to net zero. By virtue of its modularity and simple design, Helical energy believes that RiPR technology is suited to international export. In line with the Prime Ministers 10-point plan, exporting RIPR would strengthen our ability to help bring other countries to net zero and position Britain as a leader in clean technology (3).

Throughout this expansion, the following will be addressed:

i. Scaling feedstock supply and logistics with RiPR capacity
ii. Developing hydrogen storage and distribution
iii. The logistics of carbon dioxide and long-term storage

By virtue, the RiPRs, bespoke, flexible and modular design approach will comply with the government's H2BECCs strategy as it develops allowing the technology to be easily adapted to a wide range of applications.

That said, potential commercial models that might be considered in the future include:

1. The unit could be operated by Helical Energy
    - Site of operation could be owned or rented
2. RiPR could be sold and operated by third parties
    - Helical energy could offer operation and/or maintenance services for a fee
    - In this instance a revenue share model could be adopted between Helical Energy and third parties

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