Tetronics Hydrogen Plasmolysis Production Feasibility Study Report

Customer: BEIS Hydrogen Supply 2 Competition

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Contents

1 GLOSSARY

A glossary of all terms and abbreviations used in the report

BEIS – Department for Business Energy and Industrial Strategy
CAD – Computer Aided Design
CAGR – Compound Annual Growth Rate
CAPEX – Capital Expenditures
CFD – Computational Fluid Dynamics
FEA – Finite Element Analysis
GIP – Global Industrial Partner
HYS2 – Low Carbon Hydrogen Supply 2
IP – Intellectual Property
ISO – International Organization for Standardization
KPI – Key Performance Indicator
OPEX – Operational Expenditures
PEM – Polymer Electrolyte Membrane
PLC – Programmable Logic Controller
RAM – Risk and Methods
SCADA – Supervisory Control and Data Acquisition
THP – Tetronics Hydrogen Plasmolysis
TRL – Technology Readiness Level

2 EXECUTIVE SUMMARY

Tetronics Hydrogen Plasmolysis (THP) is a novel approach to producing green hydrogen. The technology combines hydrogen production from the plasma-induced thermal breakdown of water with the electrochemical breakdown typical of electrolysis. Therefore, Plasmolysis has been shown to exceed the hydrogen yield of electrolysis at a given power input.

Plasma assisted electrolysis has been a subject of academic interest but, up until now it has only been investigated by a handful of researchers at bench scale. These bench scale tests have reported hydrogen yields greater than the theoretical limit of electrolysis. In this Phase 1 project, Tetronics aimed and succeeded in developing a prototype scale Plasmolysis system which incorporated Tetronics' expertise in plasma systems design. This expertise was key in engineering a system able to operate consistently and stably as opposed to only short tests undertaken by previous researchers.

The Phase 1 project has resulted in the design, commissioning and testing of a Plasmolysis prototype system. The 14 kW_e system met the project goals of significantly increasing the scale of Plasmolysis and demonstrating stable operation and hydrogen production. The system incorporated various safety aspects into the design whilst including instrumentation to monitor its performance and the quality of the products.

The trials were designed to identify optimum plasma operating conditions and electrolyte chemistry to determine the best hydrogen production rates and the energy requirement. These results will be used as a baseline as the technology is scaled up to a demonstration plant and beyond.

The results showed the system produced hydrogen at a rate of up to 25-28 g H_2/kWh equivalent to 36 – 40 kWh/kg H_2. This indicates that the technology could outperform electrolysis systems which typically require 47 – 66 kWh/kg H_2. The levelised costs were a positive indication of future commercial potential of the technology (5.87 £/ kg H_2). Based on the hydrogen quality, a high purity hydrogen would be achievable with a combination of process modifications and integration of the system with conventional hydrogen purification unit operations, similar to those used in typical electrolysis plants.

The outcomes of the Phase 1 trials have increased the Technology Readiness Level of the THP process from 4 (bench scale testing) to 6 (a prototype system tested in a relevant environment). This system will act as a steppingstone to scale up the technology to an envisioned 300 kW_e (stack of six 50 kW_e cells) fully integrated demonstration plant for Phase 2 of this project. This demonstration plant will then act to facilitate the on-ward commercialisation of the technology and the development of larger, full-scale systems capable of contributing to the hydrogen economy.

3 OVERVIEW OF THE PROJECT

With increasing emphasis on climate change and the wider impacts of global warming as well as the ever-rising cost of fuel and energy security, considerable effort has been placed on moving away from fossil fuel reliance, with legislative and fiscal drivers encouraging a move towards renewable energy sources. As part of the UK's low carbon strategy, there has been a push to explore the production of hydrogen, specifically green hydrogen, as an alternative solution.

Tetronics' innovative Plasmolysis technology combines its decade's worth of experience in plasma torches with water electrolysis. This technology has been dubbed "Plasmolysis" and utilises the heat of the plasma to induce thermolysis of water in addition to electrolysis, resulting in increased hydrogen yield. However, the technology would not simply result in an additive benefit, but a further benefit as a result of the 'plasma effect', which is postulated to activate novel energy saving pathways reducing the hydrogen specific energy bill.

The Phase 1 study aimed to develop a Plasmolysis system capable of operating for an extended period as opposed to the short (<10s) experiments conducted by previous researchers. This was to demonstrate the technology as a real-world alternative to electrolysis which was considered to be an appropriate 'counterfactual' technology for green hydrogen production i.e. industrial take-up of electrolysers over Plasmolysis systems during the development of the hydrogen economy. The key objectives of Phase 1 are outlined below.

- Develop a 14 kW_e Plasmolysis system integrating Tetronics plasma technology through Tetronic's New Product Introduction system which requires a full engineering design as well as thorough safety reviews including HAZID and HAZOP studies.
- Build, commission and test the system with a range of instrumentation to record hydrogen production, composition and energy requirements.
- Demonstrate stable Plasmolysis operation and stable hydrogen production to increase the TRL from 4 to 6 and allow for the technology to be benchmarked against electrolysis systems.
- Through design, commissioning and operation of the 14 kW_e system, develop a blueprint for further scale up to produce a 300 kW_e demonstration system.

The basis for the technology lies in the expertise that Tetronics has with plasma technology, including its patented plasma torch design. There were two main methods flagged as potentially viable to generate hydrogen with plasma. The first was to use the intense UV light generated from plasma to crack hydrocarbons to generate hydrogen, via a type of gasification or reformation. However, as this process inherently relies on solid hydrocarbons fuel / feed materials, it will be difficult to produce green hydrogen. As such, the second method of Plasmolysis was chosen which primarily uses water as a feed material.

The Plasmolysis unit consists of two separate chambers or “cells”. The cathode cell produces a product gas that is rich in hydrogen whilst the anode cell produces a gas that’s enriched in oxygen. The cathodic torch enters through the roof of the cathode cell and in the anode cell is immersed in the electrolyte solution. CAD images and photographs of the Plasmolysis Cell and control system are shown in Figure 3-1 and Figure 4-1 respectively.

The experiments achieved its aim of benchmarking the Plasmolysis cell against a traditional electrolysis cell in order to determine the differences in energy efficiency and specific hydrogen generation rate. An appropriate commercial benchmark was identified as a PEM electrolyser cell which currently operates at 15-20 g H_2/kWh. As planned, the cell was configured to operate in both electrolysis and Plasmolysis modes to allow for comparison based on the same scale of equipment. However, the experimental data compared favourably with commercial PEM electrolysis equipment data and therefore this was used as the counterfactual. The comparison with a commercial benchmark was beneficial to understand the impact of the Plasmolysis system rather than compare against electrolysis results from a rig which has not yet been through the various optimisation and development cycles of a commercially available technology.

Figure 3-1: Plasmolysis cell. Core equipment render (LHS)

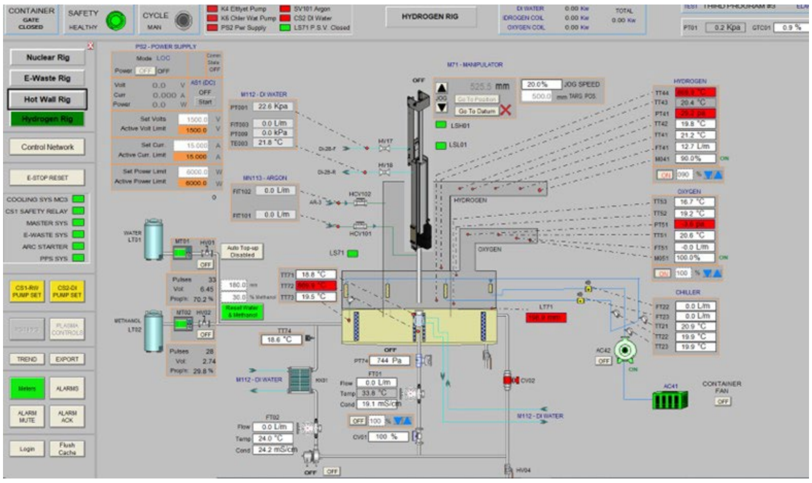
4 TESTS PERFORMED, RESULTS ACHIEVED AND CONCLUSIONS

4.1 Description of tests

During the months of July and August 2022, Tetronics built and commissioned its 14 kW Plasmolysis Cell in Swindon, UK. The facility was subject to safety and operational design considerations and was systematically commissioned to a documented procedure. The facility utilised a quadrupole gas mass spectrometer, four optical spectrometers, an internal cell camera and a PLC/SCADA based control system. The cell was successfully taken into operation in early September and trials were conducted in accordance with a prepared experimental plan. A photograph of the installed system is provided in Figure 4-1 alongside a view of the control system.

As with many new technologies, they need to be experienced and learnt from, and THP was no exception. For Tetronics, the rig operation was counter intuitive being of a high-voltage, low-current profile and with the return electrode or workpiece taking the form of an aqueous electrolyte. Very promptly, the cell was operating stably at a scale, powers and for durations which were orders of magnitude higher than achieved before in the cited prior art. The Plasmolysis cell was operated and maintained routinely. Equipment stability and longevity far exceeded previous attempts with the advanced thermal management of the cell and the integral plasma device. As an example, the cathode torch tungsten electrode showed no visible wear over the entire experimental campaign, which is in stark contrast to the seconds of lifetime achieved in other researchers' previous work.

Tetronics' Plasmolysis Cell



Tetronics Plasmolysis SCADA interface

Figure 4-1: Installation and SCADA Photographs

To ensure safety through phased commissioning i.e., no intermixed gas evolution at the cathode cell, the rig was initially operated in an electrolysis configuration. Positive performance allowed commercially optimised PEM systems to be used as the normalising benchmark for subsequent comparative technological assessments During this period, small optimisation adjustments were made to exhaust configurations, electrolyte level monitoring and electrical isolation. These changes were made as a result of lessons learnt and will be invaluable for achieving successful scale up.

The first matrix of tests performed were based on examining the effect of plasma discharge variables (current, volts, amps), for a fixed electrolyte profile, and therefore determining the optimal conditions for ongoing work. These optimal plasma conditions were then employed in a bid to determine the impacts of aqueous electrolyte profile, i.e. potassium hydroxide (KOH) and bio-methanol (CH_3OH) additions, on hydrogen production performance. After exploring and determining the optimal parameters, longer duration trials were conducted using these parameters in order to successfully demonstrate the longevity and stability of the process.

4.2 Test results

Key hydrogen production results from the trials are shown in Table 4-1. In all instances, the variables enabling the determination of KPI's like energy efficiency, hydrogen generation rate, hydrogen composition and specific energy consumption, were acquired. In summary, plasma was established and sustained in the cathode cell workspace with a submerged electrode in the anode cell, electrically connected to the cathode cell, by a low conductivity electrolyte. Under these conditions the Plasmolysis cell gas was shown to be enriched in hydrogen and oxygen at the cathode and anode cells respectively. The addition of bio-methanol to the cell, at raised concentration levels, resulted in a step change (factor of three) in the generation rate of hydrogen gas with product concentration changing from c8% up to c40% H_2(g). The observed impact is far beyond any increase that could be attributed to the molecular architecture of methanol alone noting its concentration in the solution. The main dilutant being argon gas, intentionally admitted to the Plasmolysis cell.

Table 4-1: Summary results from the Plasmolysis trials

Parameter	Electrolysis composition		
	100% Water	90% water + 10% bio methanol	70% water + 30% bio methanol
Average power input (kW)	4.6	5.7	5.5
Observed hydrogen concentration (%)	1.2-3.1	3.0-6.4	39.7-42.8
Hydrogen production rate (g/h)	2.0-4.4	5.2-11.6	138.9-153.6
Hydrogen Specific Energy Requirement (kWh/kg)	1,260-2,683	475-1,056	35.8-39.6
Energy normalised hydrogen generation requirement (g/kWh)	0.37-0.79	0.94-2.1	25.2-27.9
Calculated hydrogen purity (%) (if argon replaced with hydrogen)	99.1-99.99	73.7-99.8	79.8-84-8

The Plasmolysis cell was configured so that the gross power input was determined from the plasma power supply (power = current x voltage). The cell had several points of heat loss the three main ones being the electrolyte, plasma torch thermal management via a heat exchanger and offgas thermal management via a chiller, both were calculated using ($MCp\Delta T$). The sensible heat of the off-gas and cell thermal losses were found to be c0.1 kW. To enable the calculations, a typical combined radiant and natural convective heat transfer coefficient of 5 W/m^2K was used for the main anode cell steel tube head space of 0.266 m^2 and a delta T of 100 °C was assumed. Because of the low current and temperature operation, cell losses were minimal with energy efficiencies exceeding

OPEX projections at >95% efficient. The mass generation rate of hydrogen was determined using the ideal gas law (pressure, temperature volume flow rate) to calculate the molar flow of product gases. When combined with the composition and the defined partial pressure output of the mass spectrometer, the mass flow rate of product hydrogen was determined. The thermodynamic minimum net energy required to form hydrogen from water is 39.39 $kWh_e/kg\ H_2$ (equivalent to 25.4g H_2/kWh_e). Tetronics' feasibility testing has determined, when operating with a bio-methanol solution, that a specific gross energy requirement of 25 – 28 g H_2/kWh_e (36 - 40 kWh_e/kg), was achieved. This is approximately a 10% improvement in efficiency beyond the theoretical minimum and significantly better (40% improvement) than PEM cell's current range of reported commercial performance 47 – 66 kWh/kg H_2.

4.3 Summary

The Plasmolysis trials were successful at demonstrating the technology at a significantly larger scale than previously reported. References to prior art can be found in the list of references in this report. Previous researchers had experimented with bench-scale systems using rudimentary plasma technology. The power input in these experiments was <300 W and their duration was typically less than 10 seconds. The scale-up of the technology using Tetronics plasma torch designed meant that power inputs of kWs were achieved and the test durations usually were around 10 minutes. Tetronics plans to utilise the Phase 1 system to conduct longer trials for design and operational development. In addition to the scale up, the safety assessment and reviews throughout the design resulting in the safe operation of the prototype which achieved compliance with the Hydrogen and Oxygen Engineering Safety Standards as well as UKCA and ATEX standard compliance.

The increase in the hydrogen production due to methanol use is not yet fully understood. However, it is unlikely to be solely due to the splitting of methanol due to electrolysis. The electrolysis of methanol results in the formation of hydrogen at the cathode and carbon dioxide at the anode through the reaction:

$$CH_3OH \rightarrow CO_2 + 2H_2$$

During the trials, much of the focus of the gas analysis was on the hydrogen stream. However, where the analysis of the anode gas was performed, an oxygen enriched gas was determined which would have been formed by the electrolysis of water in the electrolyte. However, as there were some operational difficulties in switching the analysis between the cathode and anode (lagging, contamination etc.) the focus of the analysis was directed towards the cathode gas.

The analysis of the species formed around the plasma indicate the contribution of the thermal breakdown of components in the system. Methanol is more easily vaporised by the plasma than water, allowing the vapour to interact with the plasma in the gas phase. This results in the thermal breakdown of methanol which is evidenced by the presence of some by-products in the products gas such as methane and carbon dioxide as well as species observed by the optical spectrometry (OH ions).

The combination of the optical spectrometry data and the mass spectrometry data provides evidence that the hydrogen production was due to a combined effect of both the electrolysis of water / methanol and the thermolysis of water / methanol. The presence of methanol is likely to have enhanced the thermolysis due to its lower vapour pressure compared to water.

As such thermal breakdown of water / methanol would not have happen with electrolysis alone, i.e in the absence of plasma, this goes some way to explain the higher hydrogen yield recorded. However, more work needs to be done to understand the mechanisms of the hydrogen production and how the electrolyte composition can affect the yield.

5 DESCRIPTION OF THE DEMONSTRATION PROJECT

The Phase 2 demonstration plant will be designed to produce up to 7 kg/h of hydrogen with a 300 kW_e power input making its scale comparable to commercially available electrolysis plants. This would represent a significant increase in scale compared to the system installed in Phase 1 (14 kW_e). As well as achieving a level of scale up, it will be designed as an end-to-end system producing a hydrogen product suitable for direct use as an industrial gas. This will demonstrate the scalability of the THP technology, increase its Technology Readiness Level (TRL) to 7 and thereby creating confidence in the ability to produce large MW sized plants in-line with Tetronics' role-out plan for THP.

The Phase 2 project will include the design, procurement, building and commissioning of the 300 kW_e THP plant. Once commissioned, operational trials will be undertaken to demonstrate the technology at scale and produce data to allow for the quantification of various metrics such as hydrogen production, energy use and efficiency. These large-scale trials will allow for the process to undergo further optimisation and refinement acting as a steppingstone to develop a 1 MW_e reference plant.

The key objectives for Phase 2 would be as follows:

- Successfully demonstrate the technology at a near commercial scale.
- Demonstrate how Plasmolysis can be integrated into wider plant equipment to produce hydrogen of a suitable purity for end use.
- Generate operational data to refine calculations for the hydrogen production rates, energy use, efficiency and the levelised costs of production which offer a better comparison to current state-of-the-art systems.
- Produce operational and compliance data to support the licensing of a commercial facility.
- Develop a plant which can be used as a benchmark for further scale up and commercialisation of the technology which fits into Tetronics' role-out plan.
- Use the system as a benchmark to develop a longer-term operation technological risk and methods (RAMS) assessment for a commercial facility.

The successful development of Phase 2 would mark the advent of a scalable technology for producing green hydrogen at a higher yield than current alkaline and PEM electrolysis. In addition, the demonstration of the end-to-end plant will show that a THP facility will have a reduced CAPEX compared to electrolysis technologies due to minimal requirement for precious metals, small number of stacks for a given power requirement and significant reductions in electrical power infrastructure. The THP plant will be designed to have a longer life cycle of circa 20 years instead of the 7-11 years on average of PEM cells. This will be demonstrated by the calculation of the levelised costs of hydrogen production from a THP facility at scale showing it to be a competitive alternative to the existing technologies.

The end-to-end plant will include an upstream water purification system and downstream process units to purify the hydrogen to meet the specifications for Type E Grade 1/2 in ISO 14687. This approach will demonstrate the ability of the technology to be implemented as a 'whole plant' solution and how it could be integrated into a wider plant or infrastructure.

The industrial use of hydrogen has been highlighted as key for the transition away from fossil fuel use and the development of the hydrogen economy. In heavy industry, hydrogen can be used for power generation, heating applications and as a raw material which would result in a significant reduction in CO_2 emissions. In the UK, the industrial natural gas consumption is 113 TWh / year which results in the emission of 21 million tonnes of CO_2. This presents a considerable opportunity for hydrogen adoption in the UK as well as globally to take greater steps towards net zero targets. Large heating systems (>1 MW) in the UK account for 70% of the industrial natural gas use meaning there is an opportunity for both large scale multi-MW THP systems connected to a distribution network as well as smaller systems providing on-site fuel for site-specific purposes. Thus, for many industrial applications, a THP unit would allow for a hydrogen transition where a connection to a large gas network is not feasible. This would allow for greater access to hydrogen in the UK and around the world where production plants or facilities may be more remote or allow for the bespoke production of hydrogen to suit a specific operational need.

A key benefit of the THP plant is that it would also have a relatively low physical footprint compared to other electrolysis technologies. This would allow for the development of the facility at the point of use rather than requiring larger centralised production facilities which would require more investment in infrastructure, connections, storage and transport.

The smaller footprint of the THP plant would allow industrial users to produce on-site hydrogen for their own needs and to their own specification if needed for use as a raw material (in iron and steel making for example). Depending on the end use requirement, the purity of the hydrogen can be modified and tailored as required as there are various technologies available for refining which have their own benefits. It is likely that, at least in the short term, large gas hydrogen distribution networks would be fed by grey or blue hydrogen from steam methane reformation. The ability to have an on-site production facility will allow companies to operate with green hydrogen instead.

The THP plant will not be solely designed for industrial gas use, and it could also be used to produce hydrogen for fuel cells. The plant could be tailored to produce a hydrogen product for a specific use by offering a bespoke downstream purification system. The focus of the Phase 2 project will develop a hydrogen product to produce industrial gas as this may be a quick route to market to support many heavy industrial strategies to achieve a net zero target.

6 DESIGN OF DEMONSTRATION

The operation of the Plasmolysis system in Phase 1 has provided key information on the performance of the system. The Phase 1 system will be used in further trials designed to guide the scale up of the plant as well as to improve its performance. Various lessons learnt from the Phase 1 trials will inform further design improvements of the cell. There will be some modifications to the plasma torch design to better reflect its operational environment and the plasma gas (argon) will be replaced with hydrogen which will improve the purity of the output gas whilst offering wider functional benefits.

Based on the performance of the Phase 1 system, the demonstration plant will include a stack of six 50 kW_e Plasmolysis cells with a combined power input of 300 kW_e. These cells will be connected to a single upstream water purification and supply unit and a single downstream hydrogen purification process. The hydrogen purification process will be designed to remove key impurities from the hydrogen produced from the Plasmolysis cell which were identified in the gas analysis data produced in Phase 1. These impurities will include oxygen, potassium hydroxide and water. Each of these impurities will be removed from the gas in separate units consisting of a catalytic deoxidiser, a wet scrubber and dryer. These purification units are based on well-known commercially available technology and are similar to those which would be typically employed for electrolysis systems. The removal of the impurities will be undertaken to meet the requirements outlined in ISO 14687 for Grade E type 1/2 hydrogen.

CAD drawings of the Phase 2 design are shown in Figure 6-1 to Figure 6-3. The core of the system will be the stack of Plasmolysis cells. To achieve the 300 kW_e input, there will be six 50 kW_e cells. This will result in an individual cell scale up from 14 kW_e to 50 kW_e and demonstrate how multiple cells can be operated in parallel. The approach to scaling up the technology for Phase 2 will provide further learning of the scaling parameters important for the cell design to ultimately achieve a higher power input with fewer cells to reduce the plant's footprint. These parameters will include power density per unit area, flow and pressure considerations in the cell whilst plasma is operating among others.

The water purification system is required to be able to replace water consumed by electrolysis on a continual basis whilst the Plasmolysis system is operational. Based on the power requirements of the 300 kW_e system, approximately 60 kg/h of water will be needed. Raw water will be supplied from the mains and purified to produce water of a purity compliant with ASTM Type I (>18 MΩ/cm), which is the optimal purity for electrolysis systems. Based on the technology available, the flow rates required and the this would be achieved using a reverse osmosis system and a reservoir tank which will allow for water distribution.

In the Phase 1 system, the Plasmolysis cell was installed within half an ISO container. The Phase 2 system will be designed so that the 6 Plasmolysis cells fit within a single, full 40 ft, ISO container maintaining the system's small footprint. The ancillary equipment and downstream purification system will be located outside of the container within Tetronics trials facility.

The bank of plasmolysis cells will produce approximately 70 Nm^3/h of hydrogen in a gas stream containing some impurities. The downstream plant equipment has been specified for this flow rate. However, more detailed design will be undertaken to determine the exact flow rates and equipment sizing.

The scrubber unit is designed to remove potassium hydroxide from the gas stream. This component may have volatilised in the cell and if present may cause downstream corrosion issues. The initial design of the scrubber consists of two open-spray columns in series with co-current and counter-current spraying nozzles to clean the gas. The spray nozzles will simply use water to remove the potassium hydroxide due to its solubility. The two scrubbers in series will enable the concentration of the potassium hydroxide to be reduced to a level required for the integration with downstream equipment would be 5 mg/Nm^3.

In between the scrubber and the deoxidiser / dryer system a compressor has been installed. This is because the minimum operating pressure of the deoxidiser system is 10 barg, but optimally 30 barg. The operation of the plasmolysis cells does not produce a gas of such high pressure and so the pressure would need to be increased in order to achieve the optimal performance of the purification unit. The compressor would be a multi-stage system which can be configured to achieve an optimum downstream pressure. Including a compressor would allow for the process to be flexible to enable gas storage / bottling to be introduced downstream of the purification system.

The purification system will be specified to remove oxygen and water from the hydrogen. It would be the final stage of purification before use. At the scale of the demonstration system, the equipment which have been specified for this plant are a catalytic deoxidiser and a heat regenerative dryer.

The catalytic deoxidiser uses a palladium catalyst on an alumina support which removes the oxygen via a reaction with hydrogen forming water. The system will achieve an oxygen concentration in the output of 1 vpm. The water will be subsequently removed in the dryer.

The heat regenerative dryer removes the water from the gas stream via a desiccant. The system contains two vessels operating in a cycle. At any one time, the process gas will be passed through to remove the water in one vessel whilst the other is being regenerated by heating. The process will cycle between the vessels to maintain the water removal efficiency. The output requirements for the product gas are to have a dew point of -10°C which can be met by this system which can achieve a dew point of -60°C.

Due to the product gas containing hydrogen, the plant equipment will be ATEX rated and compliant with the relevant safety standards to ensure safe plant operation. The suppliers which have been contacted regarding the equipment are experienced in developing systems for hydrogen processing and are aware of the safety requirements.

The system will produce a hydrogen suitable for heating / power applications which will be shown by using the purified gas product directly in a hydrogen burner on-site. The hydrogen burner will be installed into an existing combustion chamber at Tetronics facility and will have a power duty of 200 kW based on the available hydrogen gas produced from the Plasmolysis system.

Various instrumentation will be included in the plant design to monitor the hydrogen gas production rates and determine its purity before and after downstream purification.

The plant will be installed at Tetronics' trials facility in Swindon which has the available space and infrastructure to install the system whilst minimising costs of the project and maximising value for the UK taxpayer. A plot layout showing where the system will be installed at the facility is shown in Figure 6-4. The Plasmolysis system will be based on the system which was installed during Phase 1 and will be supported by FEA/CFD analysis based on a model validated using the Phase 1 work.

The system will be able to be used as a demonstration system in future commercialisation of the technology. This will allow for trials to be undertaken as well as allow for future plant modifications to change the downstream purification system or install a system to store the hydrogen in bottles.

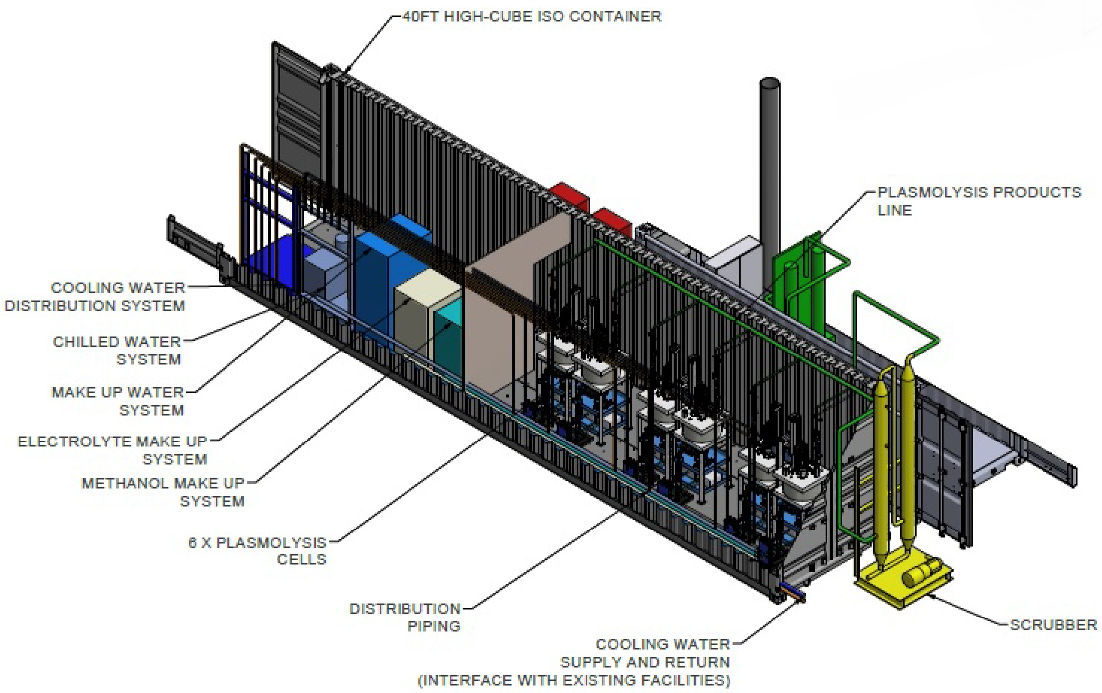


Figure 6-1: Phase 2 300 kWe layout design (plasmolysis cell view)

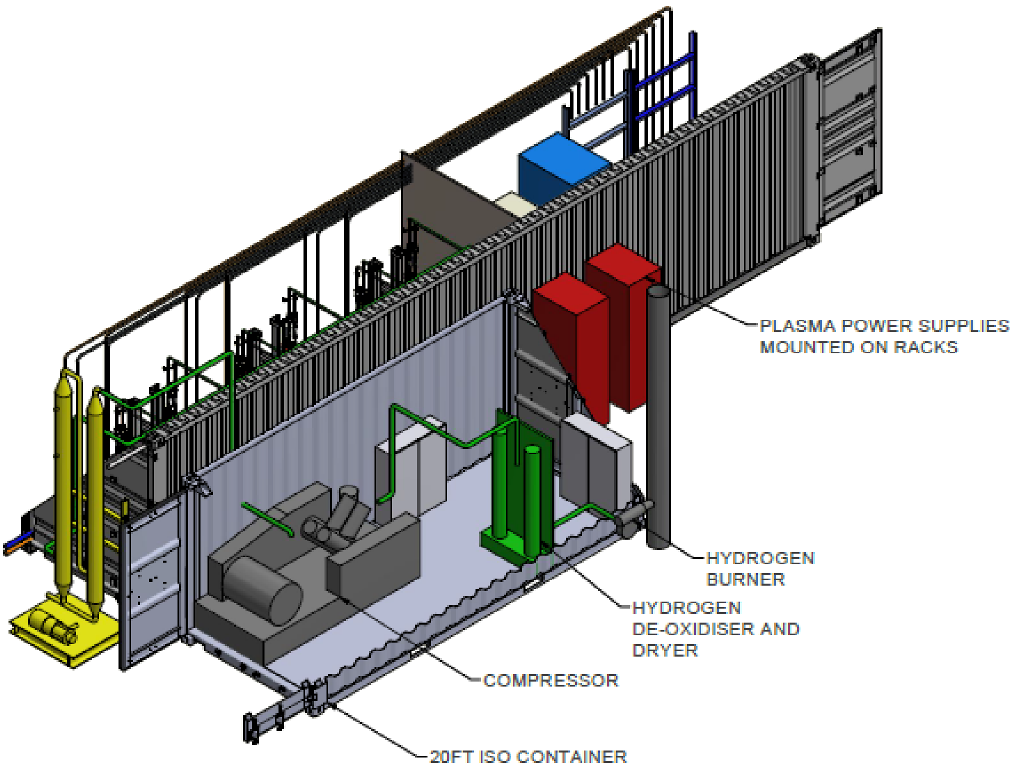


Figure 6-2: Phase 2 300 kWe layout design (purification system view)

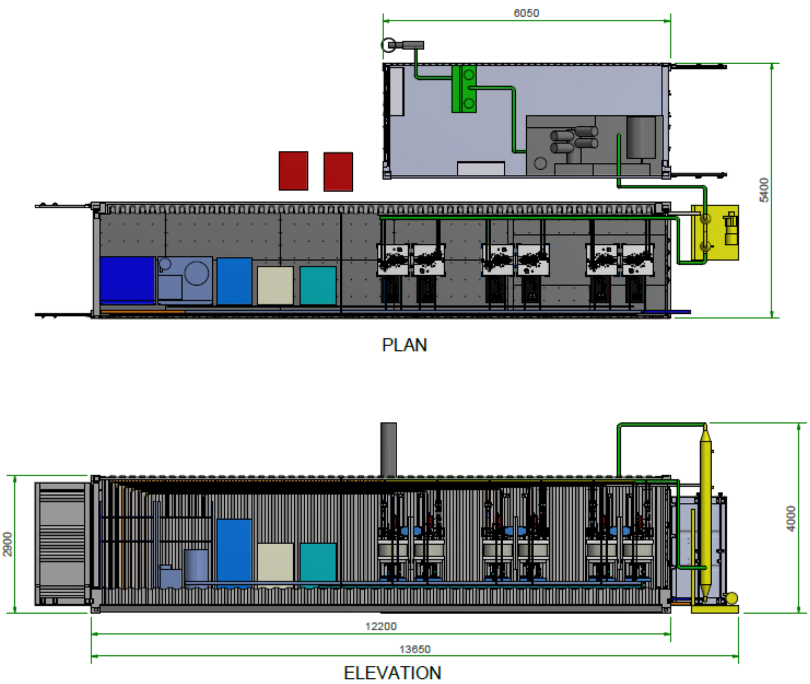


Figure 6-3: Phase 2 demonstration plant dimensions

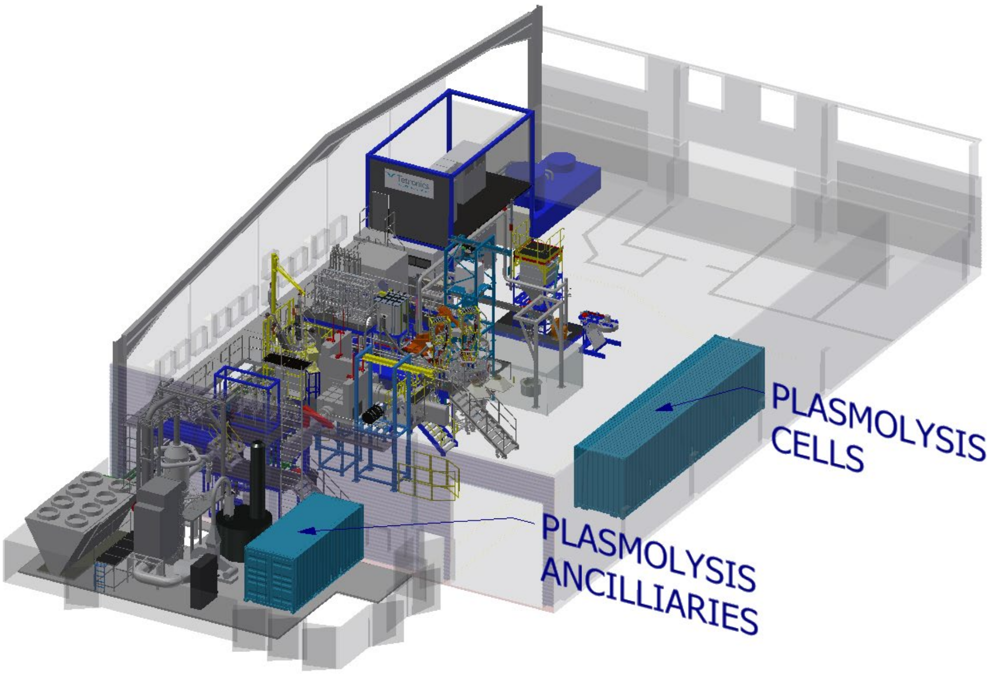


Figure 6-4: Phase 2 plot layout in Tetronics' trials facility

7 BENEFITS AND BARRIERS

7.1 Benefits of the technology

THP is a novel technology for production of green hydrogen. The technology offers an improvement over electrolysis due to the combination of the electrochemical and thermal splitting of water. The commercialisation of THP would create greater competition for green hydrogen production which currently is dominated by electrolysis processes. The Phase 1 results are very promising and demonstrate the production of hydrogen using plasma at a scale much greater than previously shown in the literature.

The results of the trials were positive as the data indicates that the hydrogen produced from Plasmolysis is achieved between 25-28 g H_2/kWh when using bio-methanol combined with water. This provides evidence of the combined effect of the plasma-based hydrogen production is occurring alongside electrolysis and the energy requirement for the process shows a 40% improvement over PEM technology.

Based on the energy requirement of the process determined through experimentation, the levelised costs of hydrogen production have been calculated. The calculation assumes that the electricity would be obtained from the grid and the Green Book costs for electricity in 2022 have been used. These costs are based on the operation of the Phase 1 trial system which will be refined as the plant is scaled up. Some uncertainties around the Levelized costs include the capital costs of the wider plant, the efficiency of the system as the plant is scaled up (which is expected to be improved) as well as other costs surrounding operational labour etc. As the technology matures, the capital cost of the system (per unit installed power) will be expected to reduce. One aspect of the technology design which will be improved will be the number of cells per MW. As the scale-up parameters are better defined and understood, larger cells should be achievable resulting in a lower CAPEX. Such improvements are likely to result in a lower levelized cost of hydrogen. Additionally, the process has not yet been optimised for hydrogen production. This means that it is possible that the system could produce a higher hydrogen output per unit energy. This would reduce the energy requirement for the system, which has the largest impact on the operational costs. The additional improvements in the outputs would further improve the levelized costs and would be determined through further work and development.

However, the preliminary results are clearly positive and show that the technology could be competitive when compared against the incumbent benchmark of electrolysis technologies like PEM electrolysers (2.5 – 7 £/kg H_2) which have already undergone process optimisation and improvements to reduce the costs of the technology.

The planned demonstration unit will have a power input of 300 kW_e, which based on the Phase 1 trials data would have an output of 7 kg/h of H_2. This is greater than the equivalent amount produced by a PEM electrolyser (6 kg/h). The predicted production rates would mean that a 300 kW_e THP plant would produce between 1840 and 2360 MWh H_2 (LHV) per year which is of a significant scale and comparable to existing commercial technologies. The roll-out plan for the technology is outlined in Section 8 which identifies that commercialised THP plants are likely to be a mixture of 1 MW_e and 10 MW_e systems. A 1 MW_e plant would produce just under 186 tonnes of hydrogen annually which equates to 6 GWh H_2 (LLV) per year. A 10 MW plant would produce approximately 60 GWh H_2 (LLV) per year. By 2030, Tetronics envisages at least one of each scale plant to be in operation demonstrating the technology will be contributing towards the government’s 1 GW installed capacity vision. However, beyond 2030, Tetronics predict a significant roll out of the technology, increasing the installed capacity to 2035 and beyond.

Based on assumptions regarding the acceleration of the technology and the achievable build rate, Tetronics predict that by 2035, there could be a combined THP installed capacity of 400 MW across a variety of small and large scale plants. Such a capacity would be able to produce 2.5 TWh / H_2 (LLV) per year.

Comparing a PEM plant producing 6 kg/h with an equivalent THP plant, there would be a 29% saving in the tCO_2e emissions operating the THP plant. This is due to the lower electricity requirement per kg of hydrogen for the Plasmolysis system. A comparison between the CO_2 emissions from the two plants is shown in Figure 7-1. The figure compares the CO_2 emissions from both a THP plant and an equivalent PEM plant. Both systems are assumed to be operated by grid electricity and the carbon emissions from the grid are calculated using BEIS Green Book guidance. If both systems were run on 100% renewable energy, there would be still some benefit from the THP plant due to the higher hydrogen output per unit energy. Therefore, to achieve a specific hydrogen production rate, a smaller plant would be required with a lower demand for renewable energy which may be provided by on-site infrastructure with associated costs i.e. on-site renewable energy plant.

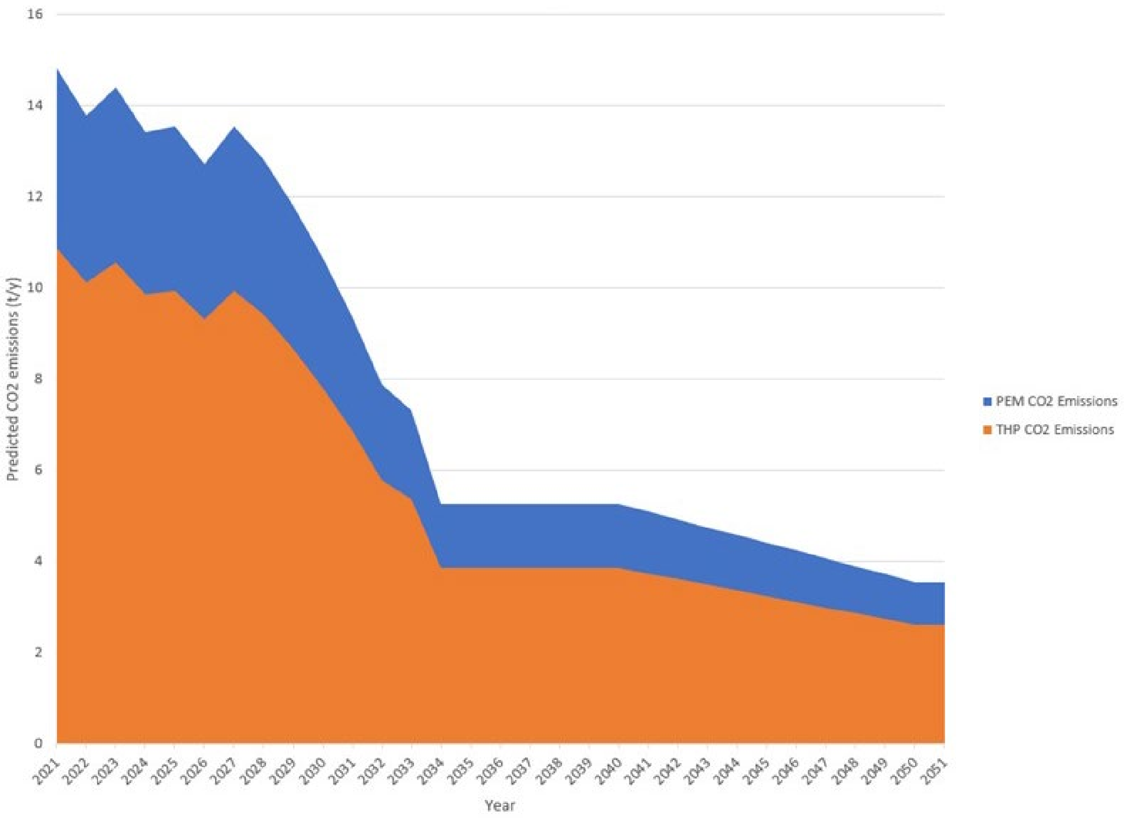


Figure 7-1: Predicted CO_2 emissions over time based on a 6 kg/h H_2 output

As the technology develops towards full commercialisation, the engineering knowledge will be developed to result in hydrogen production systems with a small footprint, smaller than electrolysis with a superior hydrogen output. This would give the THP technology an advantage over electrolysis for being able to be used for a variety of applications including large scale bulk hydrogen production as well as smaller, more focused plants or for bespoke purposes.

The technology does not require the use of precious metals which is the case for PEM electrolysers which means that the technology would have a supply chain which contains no critical raw materials. The development of the Phase 1 project indicated that it is likely that the wider supply chain for the system could be UK centric and so creates an opportunity for wider job creation within the UK as the roll-out plan for the technology develops.

7.2 Purity of hydrogen

The THP technology produces hydrogen which will contain some impurities due to the nature of the process. This is common to all hydrogen production technologies which require downstream purification systems.

The data produced by Phase 1 of the trial has shown that the hydrogen product stream directly from the Plasmolysis cell contains hydrogen and some contaminants as shown in Table 7-1.

Table 7-1: Hydrogen product gas composition produced from the cell (methanol electrolyte)

Component	Concentration (Vol %)
Hydrogen	40.8
Argon	37.9
Water	9.3
Nitrogen	7.8
Carbon dioxide	2.8
Oxygen	0.6
Methane	0.5

The main contaminant was argon whilst other minor contaminants included carbon dioxide, water and components of air depending on the experimental trials (pure water, bio-methanol, etc.). Argon was used as a gas to stabilise the plasma and protect the plasma torch tip. This was chosen as plasma operation with argon is well defined and well known to Tetronics and so suitable for the Phase 1 system. However, plasma can be operated with various other gases including hydrogen. In the Phase 2 system argon will be replaced by hydrogen which will increase the purity of the hydrogen product stream. This is highlighted in Table 4-1 where an assumed hydrogen purity has been calculated if the argon was replaced with hydrogen. The presence of argon in the product gas is challenging for the current state-of-the-art purification processes such as pressure swing adsorption units or membrane separation units. Therefore, if argon was present in the product gas, then it may be difficult to achieve a high purity hydrogen. However, for use in industrial power applications, argon can be present at concentrations up to 50%. Nevertheless, replacing argon with hydrogen will result in a product gas of a greater purity and flexibility to be used in numerous applications.

There are various uses of hydrogen which include use as an industrial heating gas or for fuel for PEM cells or aircraft. For each of these applications, the purity of hydrogen required varies, as does the limits for various contaminants such as hydrocarbons, oxygen, inert gases etc.

As with other hydrogen technologies downstream purification systems can be put in place to increase the purity of hydrogen depending on the end user's requirements. In the Phase 2 demonstration plant, the downstream purification units will be designed to produce hydrogen suitable for hydrogen-based fuel for industrial applications.

International specifications have been developed for the purity requirement of hydrogen for various applications. The ISO standard ISO 14687:2019 Hydrogen fuel quality – Product specification outlines the purity required for industrial gas applications and the limits for specific contaminants.

The key contaminants in the hydrogen produced from the THP process are oxygen and water. These components can be removed with well-known and commercially available technology. Therefore, the Phase 2 plant will have a deoxidiser and dryer to remove both oxygen and water respectively to a level which is acceptable based on the standards.

7.3 Key barriers and challenges

A key barrier to the commercialisation of the technology is the acquisition of sufficient funding to scale up the technology and prior to the development of a fully commercial scale plant. Without government funding the counterfactual would be that Tetronics would look to seek funds from private industrial partners or equity funds which would take time and would risk IP leakage.

Although Tetronics have built partnerships with industry for other plasma technology systems, these systems were typically more well established and so represented a lower risk. The THP process is novel and is currently less mature than current state-of-the-art hydrogen technologies. Typically, industrial partners can be cumbersome and risk adverse and therefore slow to react to new opportunities. This means that the time for Tetronics to acquire funds for development of the scaled-up process is likely to be elongated which may result in the technology becoming less competitive or attractive against electrolysis due to wider global learning and development.

Therefore, the use of Government funding to develop the 300 kW_e demonstration plant would result in allowing Tetronics to further develop the technology and reducing the risk of investment for private partners for the next stage of the roll-out plan, a 1 MW reference plant.

To further de-risk the investment required for the development of the future reference plan, there must be a commitment from Government policy to provide long term incentives to the development of the hydrogen economy. This would encourage market investors / funders, companies and consumers to adopt and use hydrogen in the future. The allocation of Government support to help establish the hydrogen market in the UK by overcoming the initial risks and technical challenges would allow it to become competitive against alternative energy and fossil fuels.

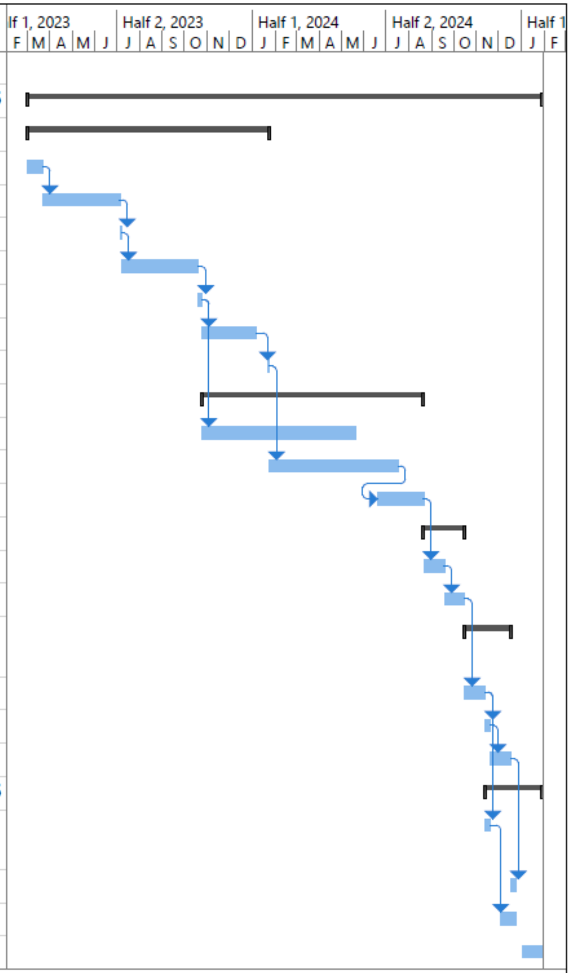
For green hydrogen to be produced there must be sufficient availability of renewable power to deliver the full environmental benefits. Therefore, the hydrogen economy should be developed alongside developments to increase renewable energy supply otherwise the ‘electrification’ of domestic and industrial operations will rely on natural gas usage and so limit the reduction of the UK’s carbon footprint.

One of the barriers for the technology is that there may initially be slow market uptake of the technology due to its perception as being complex i.e. use of plasma compared to other technologies. This may mean that companies would be reluctant to invest in the technology without it being proven at a sufficient scale. This supports the need to develop the 300 kW_e demonstration system which would be at a scale likely to develop confidence that the technology can work effectively on a commercial basis. Developing the demonstration unit will result in additional engineering design learning on the basis of the system to allow for greater simplicity in the design for future plants, for example a reduced number of THP cells. This should reduce the complexity of the design and when coupled with the anticipated higher hydrogen yield, demonstrate THP as an attractive investment opportunity.

8 COSTED DEVELOPMENT PLAN

8.1 Project Delivery Plan

ID		Task Mode	Task Name	Duration	Start	Finish
1						
2			**BEIS Phase 2 THP Demo Plant**	**501 days**	**Wed 01/03/23**	**Wed 29/01/25**
3			**Design Phase**	**235 days**	**Wed 01/03/23**	**Tue 23/01/24**
4			Concept Design Phase	15 days	Wed 01/03/23	Tue 21/03/23
5			Preliminary Design Phase	75 days	Wed 22/03/23	Tue 04/07/23
6			Preliminary Design Review (PDR)	2 days	Wed 05/07/23	Thu 06/07/23
7			Detailed Design Phase	75 days	Fri 07/07/23	Thu 19/10/23
8			Detailed Design Review (DDR)	2 days	Fri 20/10/23	Mon 23/10/23
9			Final Design Phase	54 days	Tue 24/10/23	Fri 05/01/24
10			Final Design Review (FDR)	2 days	Mon 22/01/24	Tue 23/01/24
11			**Manufature & Assembly**	**216 days**	**Tue 24/10/23**	**Tue 20/08/24**
12			Long Lead Procurement	150 days	Tue 24/10/23	Mon 20/05/24
13			General Procurement	125 days	Wed 24/01/24	Tue 16/07/24
14			THP 300Kw Cell Assembly	45 days	Wed 19/06/24	Tue 20/08/24
15			**Installation & Commissioning**	**40 days**	**Wed 21/08/24**	**Tue 15/10/24**
16			Demo Plant Installation	20 days	Wed 21/08/24	Tue 17/09/24
17			Demo Plant Commissioning	20 days	Wed 18/09/24	Tue 15/10/24
18			**Demo Plant Performance & Validation Testing**	**45 days**	**Wed 16/10/24**	**Tue 17/12/24**
19			Performance and Validation Test	20 days	Wed 16/10/24	Tue 12/11/24
20			Post Validation Test Adjustments	5 days	Wed 13/11/24	Tue 19/11/24
21			Durability Testing	20 days	Wed 20/11/24	Tue 17/12/24
22			**Analysis & Reporting**	**56 days**	**Wed 13/11/24**	**Wed 29/01/25**
23			Analysis of Performance & Validation Testing	5 days	Wed 13/11/24	Tue 19/11/24
24			Analysis of Durability Testing	5 days	Wed 18/12/24	Tue 24/12/24
25			Preparation of Final Report	15 days	Wed 04/12/24	Tue 24/12/24
26			BEIS Approval of Final Report	20 days	Thu 02/01/25	Wed 29/01/25



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8.2 Demonstration Phase Cost Estimates

ITEM	DESCRIPTION	Estimated % of Total Cost
1	**LABOUR COMPRISING:**	**40%**
1.1	**Engineering** -Comprising Design, Integration, Installation, Commissioning, Qualification Testing & Period of Continual Operation	
2	**MATERIALS COMPRISING:**	**60%**
2.1	**300kW (7kg/hr) THP System** – comprising qty. 6 Plasmolysis Cells, supporting ancillaries of power, cooling, gases, ventilation, containment etc.	20%
2.2	**Down Stream H2 Conditioning Equipment** – Comprising Flash Separator, Scrubber, Compressor, Deoxidiser, Dryer and Flare or Storage Tank	20%
2.3	**Balance of Plant & Facilities Preparation**	20%
	Total Estimated Cost	**£3-4m**

8.3 Business Plan Summary for Development Beyond Demonstration Phase.

8.3.1 Business Plan Phased Approach

Following completion of HYS2 Phase 2, TTL will have built an industrial scale demonstration plant that has upscaled the original design from the Feasibility Phase, and produced hydrogen at industrial scale, significantly reducing any technical and scale up risks whilst realising CAPEX and OPEX efficiencies. At this point, THP will be proven at scale and able to secure project finance to build a 1MW$_e$ reference plant. The following steps will be taken to develop THP beyond the demonstrator.

Step 1a – Secure Investors and / or Project Finance to build a 1MWe reference plant in the UK to operate on a commercial basis.

Step 1b – In parallel with Step 1a, TTL will develop, promote and market globally, smaller scale THP Fuel Points, based on the demonstration plant.

Step 2 – Secure investors / global industrial gas or energy industry partner(s) to build a 10 MW$_e$ global reference plant

Step 3 – Build a UK THP cell manufacturing facility to satisfy the global demand for the THP cells and the smaller scale fuel points

8.3.2 Development Cost Estimates

The development cost estimates for each step are shown below

- Step 1a - £3-5 million.
- Step 1b - £2-3 million.
- Step 2 - £15-20 million.
- Step 3 - £3-5 million.
- Total - £23-33 million

9 ROLLOUT POTENTIAL

(THP) technology is a competitive, scalable, energy efficient, low environmental impact, green hydrogen supply solution based on a unique and inventive assembly and configuration of known technologies. It has a very strong potential to be an enabler in the effective supply of affordable hydrogen; the main techno-economic challenge associated with the uptake of green hydrogen in energy systems.

9.1 Assessment of Global Electrolyser Market

A recent report by Global Market Insights https://www.gminsights.com/industry-analysis/electrolyzer-market sizes the Global Electrolyser Market at USD 5 billion in 2021 and is projected to expand at a CAGR of over 33% from 2022 to 2030. The continuous development of reliable and advanced technological power solutions in line with rising deployments of clean hydrogen generation methods will drive the market growth. The increasing consumer shift toward environmental security and supply independency coupled with the large-scale integration of renewables will sway the industry trend.

The same report predicts a Market Value (2030) for ≤500 kW electrolyser capacity segment to reach USD 276 million revenue by 2030. Growing investments across private and public sectors for the development of hydrogen infrastructure in line with ongoing developments of several projects primarily across industrial & mobility applications will fuel the industry dynamics. Moreover, a rising shift toward the adoption of eco-friendly energy sources to address increasing carbon emission concerns will propel the market demand.

The Europe electrolyser market is expected to register significant growth during the forecast timeframe, due to favourable government incentives, policies, and norms for infrastructure growth along with increasing consumer inclination toward the adoption of secure renewables. In addition, the rising electricity demand across various domestic, commercial & industrial facilities coupled with a growing focus on alternative power sources will accelerate the market growth.

9.2 THP's Position in the Global Electrolyser Market

TPH is an anticipated substitute for any electrolysis installation but has the additional advantage of being scalable, with a smaller physical footprint, and therefore deployable in remote 'off-grid' location which dramatically reduces hydrogen transportation costs in addition to energy savings.

The core THP process can be integrated into a flexible downstream process tailored to produce hydrogen at grades dependent on the end user's requirements. This means that the key characteristics of the THP technology allow it to be used in diverse hydrogen applications, both for industrial use for power and heating and for more purity demanding fuel cell technology. This means that the technology could be used across a wide range of industrial sectors enhancing its roll out capability.

Tetronics proposes the Rollout strategy of Step 1a, 1b, 2 & 3 defined in Section 8.

9.3 THP Route to Market

As an existing global supplier of Plasma technology with a successful exporting track record and extensive experience in conducting business around the world. The most likely route to market for Tetronics would be to be a technology supplier, designing, installing and commissioning THP plants for clients. This reflects Tetronics' usual approach to projects. Tetronics will focus on providing the core THP for both large scale centralised and small scale distributed applications. As the demand for the technology accelerates, Tetronics will grow to initially meet the demand as an equipment supplier, as well as acquiring a large manufacturing facility. However, Tetronics can, if required, adopt a model where we will employ industrial partnering and technology licencing to ensure rapid and global exploitation, generating significant export growth as well as acquiring knowledge and expertise from the electrolyser industry to assist with project execution. Adopting a licensing model may be beneficial where there is a significant demand for the technology or where there is a desire to install multiple units in a region, for example distributed fuel points, in partnership with an industrial partner like a energy company to establish a market foothold.

9.4 THP Applicability to Other Sites

The use of THP to produce hydrogen for industrial applications for heating / power or as a raw material means that there is an opportunity to install on-site hydrogen production facilities. This may be where the companies are not connected to a larger hydrogen gas network or require hydrogen for specific purposes. Industrial gas consumption in the UK for systems >1 MW is 79 TWh per year. Therefore, there is an opportunity for THP systems to be installed at sites such as furnace operators and chemical processing plants where there may be sufficient scope to install a hydrogen production facility supported by on-site energy generation. Tetronics would target these industries to install an initial volume of one plant per year growing to two plants per year over the first five years following commercialisation. An estimated revenue from these applications would be £60m over those five years.

However, for Tetronics to achieve a large market share within the industry there should be an ultimate target of developing large scale 100 MW THP plants. This would be possible once the engineering learning has developed based on the experience in building the combination of 1-5 MW and 10 MW plants outlined in the roll-out plan.

On the basis of the assumed build rate, Tetronics envisage an increase in the installed THP capacity over time. Following on the from initial development of the reference 1 MW and 10 MW plants, an accelerated roll-out of the technology is predicted. This would be in-line with an expected shift in industry toward hydrogen use. By 2035, there is likely to be a combination of several 10 MW plants with multiple 1 MW and THP fuel points. This combined capacity could reach 400 MW by 2030. The growth in the installed capacity and the breakdown of the types of plants is shown in Figure 9-1.

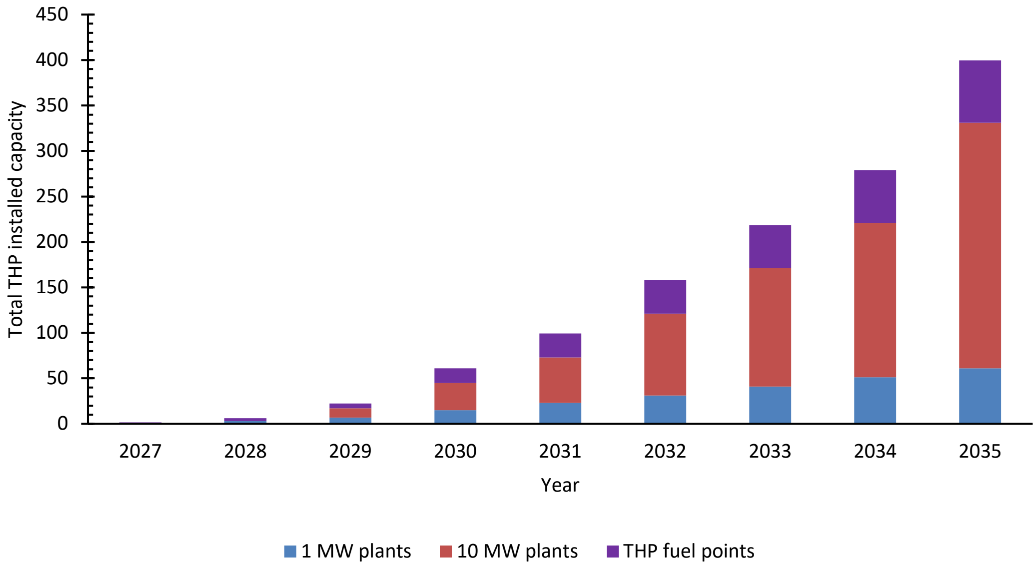

Figure 9-1: Predicted installed THP capacity to 2035

10 DISSEMINATION

Tetronics developed a dissemination plan prior to starting Phase 1. As the development of the Plasmolysis system has been completed and the test results have produced positive data, the dissemination plan can now be implemented.

The dissemination plan consists of the following activities.

10.1 Stakeholders

Beyond the BEIS and UK Government Environmental and Energy policy makers, the key stakeholders identified to fully commercialise this technology beyond HYS2 Phases 1 & 2 are global industrial partners/licensees from the gas and energy markets, both equity and project finance providers and prospective clients. The dissemination campaign will be focused on these stakeholders. Focus of the Plan

Multiple methods will be utilised to brief stakeholders on completion of Phase 1. The dissemination campaign will focus on;

- Promoting the concept, educating future potential stakeholders
- Showing how we moved things forward, reducing technology risk
- Progress made scaling up the technology, reducing scalability risk and TRLs achieved.
- Improvements in efficiency and costs reduction, improving competitiveness
- Sharing key technical achievements and economic performance, increasing awareness and investability
- Lessons learnt and challenges overcome, demonstrating we know how to progress the technology

This focus will promote the technology and create interest for the following stages of the roll-out plan. Ultimately, this interest will be important in obtaining investment to develop the 1 MW_e reference plant, key to the beginning of the commercialisation of the technology. In addition to generating interest with potential investors and stakeholders, parts of the dissemination plan will be to publish the results in scientific literature which will provide wider engagement with the hydrogen scientific community, academia and students. This is likely to promote Tetronics as a brand, potentially attracting collaborative research projects with universities which may help to further develop the technology and enhance the performance of the system.

10.2 Dissemination Plan

10.2.1 Within two months of Phase 1 completion:

- Publish a Paper in targeted and relevant Industry and technology Journals
- Create a microsite on our website and publish a case study on the Phase 1 activity
- Conduct a webinar(s) on the case study and facilitate interactive Q&A
- Conduct social media campaign to raise awareness of the technology, its benefits and the existence of the microsite, planned Webinar and future industry day

10.2.2 Within six months of Phase 1 completion:

- Hold industry day to showcase the technology to media, current and potential stakeholders whilst developing relationships with potential partners and investors required for the latter stages of the development
- Present Technology at key Global Hydrogen Economy Industry Trade Events
- Liaise with Department for International Trade to develop a capture plan to promote the technology, target overseas industrial Partners / Investors and identify potential inward investment required to fund the later stages and deliver the global role out using Industrial Partners / Licensees

10.2.3 Within two months of completion of Phase 2:

- Hold follow up industry day to show the progress made from building the demonstrator, to potential stakeholders further developing relationships with potential partners and investors required for the latter stages of the development
- Present Update on the advancement of the Technology at key Global Hydrogen Economy Industry Trade Events
- Liaise with Department for International Trade to develop a capture plan to promote the technology, target overseas industrial Partners / Investors and identify potential inward investment required to fund the later stages and deliver the global role out using Industrial Partners / Licensees

11 CONCLUSIONS

The Phase 1 study has resulted in the design, building and testing of a Plasmolysis hydrogen system. Plasmolysis is a novel method of green hydrogen production, which has previously only been investigated at bench scale. The development of a demonstration system of this size is a significant breakthrough in the engineering and design of the technology considering both the practical and safety aspects of the system.

The system was designed with considerable instrumentation to allow performance and cause and effect correlations to be determined, which has produced data regarding the characteristics of the product gas as well as the chemistry in and around the plasma arc. This work has been successful and the results show that Plasmolysis produces hydrogen due to the combined effect of plasma-induced, thermal and electrochemical hydrogen formation. This combination of hydrogen production routes is significant in that it has resulted in hydrogen production rates that exceed those of conventional electrolysis. Equipment performance has been very positively demonstrated with minimal degradation of the key plasma components, suggestive of extremely long working lives and good reliability.

Although the Plasmolysis cell is a first-of-its-kind, the limited results already show that the energy requirement to produce hydrogen and the energy efficiency of the cell has the potential to outperform comparative electrolysis systems. This makes THP process a competitive alternative green hydrogen technology. Based on the outputs of Phase 1, the costs of hydrogen production have been calculated to be £5.87 / Kg H2 which compare well with commercially available, optimised electrolysis systems (£2.5 – 7 / kg). As the process is matured through a technology development plan, the levelised costs will be reduced. Stripping away the economic treatment of the technology the best technical performance achieved was 36-40 kWh/kg H_2(g), which is better than some commercial electrolysis systems. For example, if argon is replaced by hydrogen as the plasma gas, the OPEX costs can be reduced by approximately 40%. Furthermore, carbon impact assessment based on the BEIS Greenbook methodology indicate, relative to electrolysis, a carbon saving of 4tCO_{2e} per 300 kW plant operational year equivalent to a 29% carbon saving, i.e. the scale of the proposed demonstrator.

By developing and operating the THP system in Phase 1, essential learning from experience (LFE) has informed the basis of design for further scale up. This will be used to design a 300 kW_e demonstration system which will be integrated into a wider plant system. A key objective of Phase 2 will be to demonstrate the ability of the THP plant to produce hydrogen of sufficient purity for use as an industrial fuel. The purity of the hydrogen will be improved through the use of peripheral process unit's operations similar to those used in other hydrogen production technologies as well as some possible modifications to the core Plasmolysis process.

The system designed and tested in Phase 1 has moved the TRL of Plasmolysis from 4 to 6. The next phase of the development of the technology is to increase the TRL to 7. This will be achieved through the development of the 300 kW_e integrated demonstration plant. From the development of this plant and the engineering learning and continuous improvement of the technology, this will result in improved performance and efficiencies. These improvements will ultimately have an impact on the cost of the technology (levelised costs) and make the technology both technically and therefore economically attractive. The development of the 300 kW_e plant will showcase the technology at a scale comparative with commercially available electrolysis system and will be a key steppingstone in attracting investment for larger scale, MW sized reference plants as part of Tetronics' roll-out plan.

ANNEX A. LIST OF REFERENCES

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